

Gait in Single- and Dual-Task Conditions:
Investigations of Children With and Without Developmental Risks and Disorders

Inauguraldissertation

zur

Erlangung der Würde
einer Doktorin der Philosophie

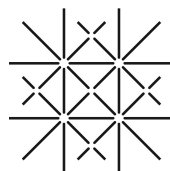
vorgelegt der
Fakultät für Psychologie
der Universität Basel

von

Olivia Manicolo

aus Münchenstein, BL

Basel, 2016



UNI
BASEL

Genehmigt von der Fakultät für Psychologie

auf Antrag von

Prof. Dr. Alexander Grob

Prof. Dr. Sakari Lemola

Basel, den _____

Prof. Dr. Roselind Lieb



ACKNOWLEDGMENTS

With lots of gratitude to the following people for their help with this dissertation:

Prof. Dr. Alexander Grob — for the guidance and the many opportunities you provided as well as the confidence you have shown in me throughout my PhD.

Prof. Dr. Sakari Lemola — for your valuable support and suggestions for my scientific work and for acting as co-referee of this dissertation.

Prof. Dr. Rui Mata — for serving on the dissertation committee.

Dr. Priska Hagmann-von Arx — for everything you have taught me. For your inspiration, guidance, and invaluable support from the moment we met.

The CoMoDe-Team — for all the time and effort you put into our research projects to make them a success.

Dr. Katrin Furler — for your encouragements throughout my PhD and your helpful comments and suggestions when proofreading my dissertation.

My colleagues — for the enriching exchange of knowledge. Especially M.Sc. Rebekka Weidmann for the positive and close collaboration.

Barbara, Robert, and Samuel Sieber, and Carole Martin — for your continuous interest in my work and your emotional support over the past years.

Jonas Sieber — for always believing in me. For your understanding and encouragement and for giving me the strength and energy I need to reach my goals.

My parents, Eva and Victor Manicolo — for your unconditional love and support in everything I do. To you I dedicate this thesis.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	III
ABSTRACT	VI
1. Introduction.....	1
2. Theoretical Background.....	3
2.1 Gait.....	3
2.2 Gait parameters and their measurement.....	3
2.3 Gait in typically developing children.....	4
2.4 Gait in children with developmental risks and disorders.....	5
2.4.1 Gait in children born very preterm	6
2.4.2 Gait in children with ASD.....	6
2.4.3 Gait in children with ADHD	8
2.5 Gait in dual-task conditions	9
2.5.1 Dual-task gait in typically developing children	9
2.5.2 Dual-task gait in children with impairments in executive functions.....	10
2.5.3 Effects of different concurrent tasks on gait	12
3. Research Questions.....	13
4. Method	15
4.1 Samples.....	15
4.2 Measures	17
4.3 Procedure	17
5. Synopsis of Results	20
5.1 Gait characteristics of typically developing children	20
5.2 Gait characteristics of children born very preterm	21
5.3 Gait characteristics of children with ASD	21
5.4 Gait characteristics of children with ADHD.....	22

6. General Discussion	24
6.1 Gait characteristics of typically developing children	24
6.2 Gait characteristics of children born very preterm	26
6.3 Gait characteristics of children with ASD	27
6.4 Gait characteristics of children with ADHD.....	29
6.5 Strengths and Limitations	32
6.6 Conclusions and Outlook.....	34
References	38
APPENDIX A: Article 1	53
APPENDIX B: Article 2.....	67
APPENDIX C: Article 3.....	86
APPENDIX D: Article 4	121
APPENDIX E: Article 5.....	127
APPENDIX F: Selbständigkeitserklärung.....	152
APPENDIX G: Curriculum Vitae	153

ABSTRACT

Gait is a complex human motor activity with walking being considered the most important mode of locomotion. Engaging in concurrent tasks while walking is routine in daily life, and although walking is a highly practiced task, dual tasking has shown to alter gait performance, revealing the involvement of cognitive processes in gait control. Yet for children, research on single- and dual-task walking is scarce. This cumulative dissertation comprises five articles that extend the research on gait in children with and without developmental risks and disorders. The samples in the research were 138 typically developing children, 44 very preterm children, 32 children with autism spectrum disorder (ASD), and 30 children with attention deficit/hyperactivity disorder (ADHD). For gait analysis (i.e., measurements of spatio-temporal and variability gait parameters) the GAITRite system was used. Single-task walking was investigated in children with ASD whereas the gait of the other children was further assessed while they concurrently performed motor and cognitive tasks. Findings for typically developing children showed an increase in gait maturation with increasing age in single- and dual-task conditions, indicating that in middle childhood gait is still developing. Further, results revealed a developmental delay in gait variability in children with ASD and ADHD, indicating that these children walk less regularly than controls. Dual tasking caused gait alterations in all children, indicating that walking is not an automatic activity but rather requires cognitive processes. Finally, in typically developing children and children with ADHD, a motor concurrent task had a greater effect on gait than a cognitive concurrent task, possibly because it competes more strongly with walking for processing resources. The present results emphasize that gait forms an important part of children's motor development with maturational changes across childhood and support the idea that cognitive processes are involved in the control of gait. Furthermore, they highlight the necessity to account for the type of concurrent task in dual-task walking paradigms and the careful selection and interpretation of the gait parameters under consideration.

1. Introduction

The human body is designed for efficient motion, which includes the bipedal gait (Keen, 1993). Furthermore, while there are various ways allowing us to independently move through our environment, the most common mode of locomotion is the walking gait (Adolph, Vereijken, & Shrout, 2003; Sparrow, 2000). Walking involves the interplay of neural and musculoskeletal systems to produce coordinated limb movements (Hausdorff, 2007). Therefore, gait performance can be an important marker of an individual's motor functioning (e.g., Lord, Galna, & Rochester, 2013). For adult samples, gait analysis has been recognized as a powerful tool for identifying symptoms of incipient pathology, tracking disease progression in clinical samples, measuring the efficacy of interventions, and predicting cognitive decline as well as falls (e.g., Amboni, Barone, & Hausdorff, 2013; Beauchet et al., 2009; Hausdorff, 2005). For children, on the other hand, research on gait has mostly concentrated on the early years of life, with the onset of independent walking forming one of the most studied milestones of infant motor achievement (Adolph et al., 2003). For the time after infancy, preliminary findings have indicated that gait analysis can reveal disorder-related walking characteristics that along with other signs and symptoms can provide important information on a child's development, including motor functioning (e.g., Drillis, 1958; Dusing & Thorpe, 2007). However, gait characteristics have so far only rarely been included in investigations of children's motor functioning during childhood. Therefore, research on gait characteristics of children at risk for impairments in motor functioning, including children with developmental risks such as very preterm birth (i.e., birth before the 32nd gestational week) or developmental disorders (e.g., autism spectrum disorder, ASD; attention deficit/hyperactivity disorder, ADHD), is only emerging.

In everyday life we usually walk and concurrently perform tasks such as fastening jacket buttons or listening to someone talk. Studies investigating adults as well as children (e.g., Hung, Meredith, & Gill, 2013; Woollacott & Shumway-Cook, 2002) have shown that

gait performance is affected in such dual-task walking conditions, indicating that cognitive processes such as executive functions are involved in the control of gait. Studies with adult samples have also revealed that gait changes related to dual tasking become stronger with increasing age and are particularly profound in neurological patients with impairments in executive functions (e.g., Al-Yahya et al., 2011; Beurskens & Bock, 2012; Sheridan, Solomont, Kowall, & Hausdorff, 2003; Yogev et al., 2005). For children, previous studies showed that effects of a concurrent task on walking decrease with increasing age, indicating that dual-task gait is still developing during childhood (Abbruzzese et al., 2014; Boonyong, Siu, van Donkelaar, Chou, & Woollacott, 2012). However, for child samples including subjects with impairments in executive functions such as children with ADHD (e.g., Wilding, 2005) or children born very preterm (e.g., Mulder, Pitchford, Hagger, & Marlow, 2009), little is known regarding the role that such impairments may play in dual-task gait.

The present dissertation aims to extend current knowledge on gait development of children with and without developmental risks and disorders. Specifically, we investigated single- and dual-task walking along with the effects of age and type of concurrent task on various gait parameters with a variety of samples: typically developing children (Article 1), children born very preterm (Article 2), children with ASD (Article 3), and children with ADHD (Articles 4 and 5).

Chapter 2 provides an overview of the existing theoretical and empirical background relevant to this dissertation. Chapter 3 presents the research questions derived from the theoretical and empirical background. Chapter 4 gives a short description of the individual studies and samples, as well as an overview of the corresponding measures and scales along with the procedures used in gait analysis. Chapter 5 comprises a synopsis of the results, which is followed in Chapter 6 by a general discussion of the main findings and suggestions for future research.

2. Theoretical Background

2.1 Gait

Gait is defined as a form of bipedal locomotion, which is achieved through the movement of different body segments and the forward propulsion of the body's center of gravity (Bruijn, Meijer, Beek, & Van Dieën, 2013). Furthermore, gait is a remarkably complex motor skill involving interactions between the neural networks in the central nervous system and the intraspinal nervous system on the one hand and the mechanical periphery consisting of bones and muscle on the other (Scafetta, Marchi, & West, 2009). That is, while neural control systems are responsible for coordinating limb movements, with muscles receiving commands from the nervous system, sensory information is also sent back that modifies the activity of the central neurons (Hausdorff, 2007; Scafetta et al., 2009). Gait assessment is therefore a useful method of exploring brain-behavior relationships by means of examining the integrity of the central nervous system, and it provides an important marker of an individual's motor functioning (Lord et al., 2013).

2.2 Gait parameters and their measurement

Gait is a cyclic activity involving a sequence of strides, which can be characterized by spatiotemporal and variability parameters (Hausdorff, 2007; Lord et al., 2013). Spatiotemporal characteristics are expressed as the mean of multiple strides and include, for example, measures of gait velocity (obtained by dividing the distance traveled by ambulation time, expressed in centimeters per second), stride length (the distance between the heel points of two consecutive footfalls of the same foot, expressed in centimeters), stride time (the time elapsed between the first contact of two consecutive footfalls of the same foot, expressed in seconds), and base of support (the perpendicular distance from heel point of one footfall to the line of progression of the opposite foot, expressed in centimeters). To account for participants' height or leg length, normalized spatiotemporal gait parameters may be used (Dusing & Thorpe, 2007; Hof, 1996; Stansfield et al., 2003). While gait velocity as a general indicator of

functional performance is the most commonly reported gait outcome (Al-Yahya et al., 2011), stride length and stride time reflect gait patterning (Gabell & Nayak, 1984), and base of support measures equilibrium (Nayate et al., 2012). Variability parameters of gait, on the other hand, reflect stride-to-stride fluctuations in spatiotemporal parameters, which are sensitive to subtle physiological changes such as neural maturation and are believed to reflect the automaticity and regularity of gait (cf. Hausdorff, 2005). One possibility of measuring variability in spatiotemporal gait parameters is the calculation of the percentage coefficient of variation ($CV = \text{standard deviation}/\text{mean} \times 100$).

Measurements of spatiotemporal and variability gait parameters can be obtained by various methods, including paper-and-pencil tests (McDonough, Batavia, Chen, Kwon, & Ziai, 2001), electronic foot switches, and video-based analysis. However, most of these methods are labor intensive and time consuming (Bridenbaugh & Kressig, 2010; McDonough et al., 2001). To improve the feasibility of assessing spatiotemporal and variability gait parameters, several electronic walkway systems have been developed such as the GAITRite system (GAITRite Platinum; CIR Systems, USA). It consists of a portable walkway with grids of embedded, pressure-sensitive sensors and allows a computerized calculation of gait parameters with proven validity and reliability for adults and children (Bilney, Morris, & Webster, 2003; Cutlip, Mancinelli, Huber, & DiPasquale, 2000; McDonough et al., 2001; Thorpe, Dusing, & Moore, 2005; Van Uden & Besser, 2004). Furthermore, it does not require the placement of any devices on the person, and subjects can wear their normal shoes and clothes, which makes it possible to assess gait performance as it is exhibited under everyday circumstances.

2.3 Gait in typically developing children

Typically developing children master independent walking, commonly defined as taking a minimum of five unaided steps, at approximately 12 to 14.5 months of age (Piper, 1994; Storvold, Aarethun, & Bratberg, 2013). The subsequent gait development is characterized by

rapid improvements over the following months (Adolph et al., 2013) until by the age of 3 years the visually apparent unsteadiness in walking has been replaced by a more stable gait pattern (Sutherland, Olshen, Biden, & Wyatt, 1988). With increasing age children show more subtle improvements in spatiotemporal gait parameters (e.g., enhanced gait velocity and step length) before reaching a mature gait pattern at about 7 years (e.g., Adolph et al., 2013; Hillman, Stansfield, Richardson, & Robb, 2009; Holm, Tveter, Fredriksen, & Vollestad, 2009). Gait variability, on the other hand, further develops beyond this age with gait becoming more regular during middle and late childhood before reaching maturity in adolescence (Froehle, Nahhas, Sherwood, & Duren, 2013; Hausdorff, Zeman, Peng, & Goldberger, 1999; Hillman et al., 2009; Lythgo, Wilson, & Galea, 2009, 2011). Thus, previous findings indicate that spatiotemporal and variability gait parameters of typically developing children seem to undergo temporally distinct developmental trajectories with gait variability showing a later maturation than spatiotemporal gait parameters. To further investigate this assumption, Article 1 of the present dissertation included spatiotemporal as well as variability gait parameters and investigated possible age-dependent differences in a large sample of typically developing school-aged children.

2.4 Gait in children with developmental risks and disorders

Numerous studies have shown that children with developmental risk factors such as very preterm birth as well as children with developmental disorders such as ASD or ADHD are more likely to show impairments in motor development, including difficulties with gross and fine motor functions and coordination, compared to their typically developing peers (e.g., Goyen, & Lui, 2009; Van Damme, Simons, Sabbe & van West, 2015). However, although such impairments in motor development can lead to alterations in movement patterns, including walking (Adolph et al., 2003; Kindregan, Gallagher, & Gormeley, 2015), gait characteristics have rarely been included in investigations of children's motor functioning, and research on gait characteristics of children with developmental risks and disorders is scarce.

2.4.1 Gait in children born very preterm. The incidence of very premature birth has been rising in the past two decades and the survival rate of children born very preterm without major impairments has increased due to improved neonatal care (Saigal & Doyle, 2008). However, even among generally well-developing preterm children there is evidence that they are at increased risk for several long-term sequels (Lemola, 2015), including impairments in motor development (De Kieviet, Piek, Aarnoudse-Moens, & Oosterlaan, 2009; Goyen, & Lui, 2009). Previous studies with preterm children have indicated that the onset of independent walking is delayed (Gabriel et al., 2009; Jeng et al., 2008; Nuysink et al., 2013). In this vein, studies with preterm infants have shown that the measure of onset of independent walking reflects various degrees of motor delay (e.g., Jeng, Yau, Liao, Chen, & Chen, 2000) and that qualitative aspects of early leg movements such as coordination may predict subsequent neurodevelopmental disorders (Vaal, Van Soest, Hopkins, Sie, & Van der Knaap, 2000; Jeng, Chen, Tsou, Chen, & Luo, 2004). Furthermore, during childhood and adolescence, preterm children show an increased risk for gross motor deficits in dynamic and static balance skills (e.g., one-leg standing or heel walking) compared to typically developing peers (e.g., Marlow, Hennessy, Bracewell, & Wolke, 2007). Hence, although motor impairments have been studied in very preterm children (De Kieviet et al., 2009; Goyen & Lui, 2009), gait development after infancy remains unexplored. The present dissertation aimed at filling this gap in research and investigated in Article 2 spatiotemporal and variability gait parameters in a sample of school-aged children born very preterm in comparison to a control group of full-term children.

2.4.2 Gait in children with ASD. For the neurodevelopmental disorder ASD—characterized by the core symptoms of impairments of social communication and repetitive behaviors with limited interests (American Psychiatric Association, 2013)—previous findings show a delayed onset of independent walking (e.g., Provost, Lopez, & Heimerl, 2007; Segawa & Nomura, 1991) as well as differences in gait parameters compared to typically developing

controls during childhood. Regarding gait variability, studies have consistently reported higher values, indicating a less regular and less automatic gait pattern, among children with ASD (Nayate et al., 2012; Rinehart, Tonge, Bradshaw, et al., 2006; Rinehart, Tonge, Iansek, et al., 2006) whereas results for spatiotemporal measures have been mixed, with some studies finding reduced stride length and increased stride time for children with ASD compared to controls (e.g., Lim, O'Sullivan, Choi, & Kim, 2016; Vernazza-Martin et al., 2005; Weiss, Moran, Parker, & Foley, 2013) and others reporting no group differences (e.g., Chester & Calhoun, 2012; Rinehart, Tonge, Bradshaw, et al., 2006). This inconsistency in results for spatiotemporal gait parameters is possibly due to differences in methodology (i.e., different gait analysis systems) and inclusion criteria (e.g., gender, age, intellectual functioning).

Furthermore, while findings on outcomes during adolescence and adulthood suggest that in most cases ASD is a lifelong condition that involves persistent impairments in mental, linguistic, social, and motor abilities (Eaves & Ho, 2008; Nordin & Gillberg, 1998; Van Damme et al., 2015), there is evidence that a small percentage of children diagnosed with ASD lose their symptoms that support a diagnosis of ASD at some point during their life (Fein et al., 2013). However, so far, it has not been investigated whether this also holds true for gait development, that is, whether gait impairments of children with ASD normalize during development or persist. Hence, important gaps in research on gait in children with ASD are evident. First, it has not been investigated whether a delayed onset of independent walking is associated with later gait development during childhood in subjects with ASD. Second, whereas recent studies indicated impairments in motor skills (for review see Paquet, Olliac, Golse, & Vaivre-Douret, 2015) and higher gait variability (e.g., Nayate et al., 2012) in children with ASD, no study has so far investigated possible associations between motor skills and gait variability. Finally, it remains unclear whether with increasing age, gait variability measures of children with ASD decrease or remain persistent and nonconvergent toward that of typically developing subjects. Article 3 of the present dissertation sought to fill these gaps

in research by examining gait performance and collecting information on early motor milestones as well as assessing motor skills of a larger sample covering a wider age range of children with ASD than in previous studies.

2.4.3 Gait in children with ADHD. A similar pattern of open research questions related to gait development during childhood emerges for ADHD—one of the most frequently diagnosed neurodevelopmental disorders in childhood, characterized by symptoms of age-inappropriate impulsivity, hyperactivity, and inattention (American Psychiatric Association, 2013). Results of two previous studies investigating gait in school-aged children with ADHD (off or without medication) found a tendency toward higher values in gait variability, such that children with ADHD showed a trend toward a less regular gait pattern compared to controls, but the two groups did not differ in gait velocity (Leitner et al., 2007; Papadopoulos, McGinley, Bradshaw, & Rinehart, 2014). However, the sample sizes in both studies were small (16 and 14 children with ADHD respectively), which may have limited their power to detect statistically significant group differences in gait variability. Furthermore, similar to the results mentioned above in the context of ASD, findings exist showing that ADHD symptoms tend to improve with age and that children diagnosed with ADHD outgrow their symptoms in adulthood (Burke & Edge, 2013; Faraone, Biederman, & Mick, 2006). In contrast, other studies reported continuation of ADHD into adulthood and found persistent symptoms of inattention, disorganization, distractibility, and impulsivity (Fischer & Barkley, 2007). However, the questions regarding persistent or improving impairments have so far not been addressed in the context of gait development in children with ADHD. Thus, the first goal of Article 4 of the present dissertation was to replicate previous results indicating a tendency toward a less regular walking pattern in children with ADHD by including a larger sample than those used in the two previous studies (i.e., Leitner et al., 2007; Papadopoulos et al., 2014). Additionally, the second goal of Article 4 was to investigate whether gait variability in children with

ADHD decreases with increasing age toward that of typically developing children or whether it remains persistent and nonconvergent toward controls across age.

2.5 Gait in dual-task conditions

Engaging in cognitive and motor concurrent tasks while walking is routine in daily life. Such dual-task conditions have been shown to alter adults' and children's gait when compared to walking without an additional task (i.e., single-task walking), indicating that although walking is a highly practiced task, the regulation of gait is not a fully automatic activity but rather requires cognitive processes such as executive functions (e.g., Woollacott & Shumway-Cook, 2002). Executive functions refer to higher cognitive processes that include the control and allocation of attentional resources necessary for adaptive planning of behaviors (Anderson, 2002). Dividing attention (e.g., as required in dual-task paradigms) can also be considered an example of an executive function task (Springer et al., 2006). Two theories have been used to explain dual-task effects on gait. The capacity-sharing theory proposes that attentional resources are limited in capacity and have to be shared between two tasks (Kahneman, 1973; Tombu & Jolicœur, 2003). Researchers have suggested that gait decrements occur when the attentional demands of the concurrent task exceed the attentional resource capacity available (Huang & Mercer, 2001; Woollacott & Shumway-Cook, 2002). In contrast, the bottleneck theory (Pashler, 1994) proposes that two tasks that are performed simultaneously can only be carried out sequentially. This poses high demands on the capacity to switch between tasks, which in turn may lead to diminished performance in one or both of the tasks. However, there is currently no agreement on which theory best explains cognitive processing and dual-task effects (Yogev-Seligmann, Hausdorff, & Giladi, 2008).

2.5.1 Dual-task gait in typically developing children. Most studies on dual-task effects on gait in typically developing children investigated spatiotemporal gait parameters such as gait velocity or stride length (e.g., Boonyong et al., 2012; Cherng, Liang, Hwang, & Chen, 2007; Hung et al., 2013), whereas only a few studies investigated gait variability. These re-

vealed inconsistent results, with some researchers reporting no effect of dual tasking (Abbruzzese et al., 2014; Katz-Leurer, Rotem, & Meyer, 2013; Leitner et al., 2007) and others showing an increase in gait variability (Schaefer, Lövdén, Wieckhorst, & Lindenberger, 2010). However, the sample sizes in these studies were small, limiting the statistical power of these analyses. Furthermore, two studies investigated age-dependent differences in dual-task gait and found that the effects of concurrent tasks on walking were stronger for younger than older children or adults (Abbruzzese et al., 2014; Boonyong et al., 2012). Hence, the investigation of age-dependent differences in dual-task gait is also the subject of the present dissertation, and Article 1 sought to extend existing research by investigating dual-task effects on spatiotemporal as well as variability gait parameters in a larger sample of typically developing children than previously studied. Finally, studies investigating children with developmental impairments have shown that children with motor and cognitive deficits are more vulnerable to dual-task gait decrements than typically developing children (e.g., Cherng, Liang, Chen, & Chen, 2009; Katz-Leurer, Rotem, Keren, & Meyer, 2011), which in turn may affect motor behavior (e.g., physical activity; Cairney et al., 2005), injury risk (Bloemers et al., 2011), and psychosocial functioning (i.e., risk of peer rejection, social and emotional problems; Bejerot, Plenty, Humble, & Humble, 2013). However, for typically developing children it remains unknown whether an association between dual-task gait effects (i.e., change in gait from single- to dual-task walking conditions) and cognition, as well as motor behavior, injuries, and psychosocial functioning, exists. This gap in research is addressed in Article 1 of the present dissertation.

2.5.2 Dual-task gait in children with impairments in executive functions. The association between gait performance and impaired executive functions was initially investigated in adult samples with recent findings showing that dual-task effects on gait and particularly on gait variability are more profound in older individuals (Beurskens & Bock, 2012) and patients with neurological impairments who exhibited deficits in executive functions (Al-Yahya

et al., 2011). It is assumed that impaired executive functions contribute to stronger effects of dual tasking on gait by limiting the ability to devote the appropriate amount of attention to walking when concurrently performing another task (Hausdorff, 2005). This may also hold true for children with impairments in executive functions, such as children with severe post-traumatic brain injury, for whom a study showed reduced gait velocity as well as higher gait variability in dual-task conditions compared to typically developing controls (Katz-Leurer et al., 2011).

Impairments in executive functions have also been reported for children born very preterm (Aarnoudse-Moens, Weisglas-Kuperus, van Goudoever, & Oosterlaan, 2009; Hagmann-von Arx et al., 2014; Mulder et al., 2009) but so far no study has investigated whether those impairments play a role in gait performance in dual-task conditions. Accordingly, Article 2 aimed at filling this gap in research by examining whether spatiotemporal as well as variability gait parameters would be more affected in very preterm than in full-term children when walking and concurrently performing tasks.

ADHD has repeatedly been linked to deficits in executive functions (e.g., Gillberg, 2003; Steger et al., 2001; Wilding, 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), which may affect walking performance in dual-task conditions. However, so far only one study has investigated walking patterns of children with ADHD in a dual-task paradigm (Leitner et al., 2007). Results showed that a cognitive concurrent task significantly altered gait performance of children with ADHD but this dual-task effect on gait was comparable between children with and without ADHD (Leitner et al., 2007). As it may have been assumed that children with ADHD would show lower gait performance compared to controls when their impaired executive functions were additionally taxed by a concurrent task (Leitner et al., 2007), Article 5 of the present dissertation aimed at shedding further light on dual-task walking of children with ADHD.

2.5.3 Effects of different concurrent tasks on gait. A previous investigation of dual-task effects on gait among typically developing preschool children showed that gait alterations are apparent for both motor and cognitive concurrent tasks but that effects on walking are stronger for a motor concurrent task compared to a cognitive concurrent task (Cherng et al., 2007). These findings can be interpreted from the perspective of the multiple-resource model of attention (Wickens, 1991) assuming that two tasks will interfere with each other if they share the same pool of resources. Hence, a cognitive concurrent task might not cause gait alterations to the same extent as a motor concurrent task that shares resources with walking (Yogev-Seligmann et al., 2008). Article 1 of the present dissertation tested this assumption for typically developing school-aged children by including a cognitive as well as a motor concurrent task while walking and investigated whether a motor concurrent task would affect gait parameters more strongly than a cognitive concurrent task. Furthermore, this assumption has so far not been investigated in children with ADHD since Leitner et al. (2007) included a cognitive but not a motor concurrent task in their study. Therefore, Article 5 aimed at filling this gap in research and investigated whether a motor concurrent task would affect gait performance of children with ADHD more strongly than a cognitive concurrent task.

3. Research Questions

The aim of the present dissertation is to extend existing research on gait development during childhood by examining spatiotemporal as well as variability gait parameters of typically developing children, children with the developmental risk factor of very preterm birth, and children with the developmental disorders ASD and ADHD. Thus, this dissertation includes investigations of walking conditions without an additional task (i.e., single-task walking) as well as dual-task conditions where children were asked to perform concurrent tasks while walking. In particular, within the scope of five articles the following research questions are addressed:

1. Gait characteristics of typically developing children (Article 1)
 - a. Is age related to gait (i.e., spatiotemporal and variability gait parameters) in single- and dual-task walking?
 - b. Does a concurrent task affect spatiotemporal as well as variability gait parameters?
 - c. Does a motor concurrent task affect gait more strongly than a cognitive concurrent task?
 - d. Are fewer dual-task gait effects related to better cognitive performance, better motor behavior, lower injury risk, and fewer injuries, as well as higher psychosocial functioning?
2. Gait characteristics of very preterm children (Article 2)
 - a. Do very preterm children differ in gait (i.e., spatiotemporal and variability gait parameters) compared to control children born full-term in single-task walking?
 - b. Does a concurrent task affect spatiotemporal as well as variability gait parameters of very preterm children?
 - c. Does a concurrent task affect gait of very preterm children more strongly compared to controls?

3. Gait characteristics of children with ASD (Article 3)

- a. Do children with ASD differ in gait (i.e., spatiotemporal and variability gait parameters) compared to typically developing control children in single-task walking?
- b. Do children with ASD and control children differ in their age of onset of independent walking and is there an association with gait variability?
- c. Do children with ASD and control children differ in their motor skills and are these skills associated with gait variability?
- d. Does gait variability of children with ASD show an age-dependent decrease and converges toward that of control children?

4. Gait characteristics of children with ADHD (Articles 4 and 5)

- a. Do children with ADHD differ in gait (i.e., spatiotemporal and variability gait parameters) compared to typically developing control children in single-task walking?
- b. Does gait variability of children with ADHD show an age-dependent decrease and converges toward that of control children?
- c. Does a concurrent task affect gait of children with ADHD more strongly compared to controls?
- d. Does a motor concurrent task affect gait of children with ADHD more strongly than a cognitive concurrent task?

4. Method

Sections 4.1 and 4.2 provide an overview of the samples, measures, and corresponding scales of each article. Section 4.3 summarizes the gait analysis procedure and includes information on the concurrent tasks the children performed while walking.

4.1 Samples

Article 1 (Hagmann-von Arx⁺, Manicolo⁺, Lemola, & Grob, 2016; ⁺shared first authorship). In Article 1 we examined whether age is related to gait characteristics (i.e., spatiotemporal and variability gait parameters) in single- and dual-task walking of typically developing school-aged children. Furthermore, we investigated whether a concurrent task affects spatiotemporal as well as variability gait parameters and whether a motor concurrent task affects gait more strongly than a cognitive concurrent task. Finally, we examined whether fewer dual-task gait effects (i.e., lower change in gait velocity and gait variability from single- to dual-task walking) would be related to better cognitive performance, better motor behavior (i.e., higher sports participation), lower injury risk, and fewer injuries, as well as higher psychosocial functioning (e.g., higher physical and psychological well-being, higher social acceptance). The sample of Article 1 was recruited from birth announcements in newspapers as well as from local schools and consisted of 138 typically developing school-aged children with a mean age of 10.0 years ($SD = 1.5$).

Article 2 (Hagmann-von Arx, Manicolo, Parkinson-Gloor, Weber, Grob, & Lemola, 2015). In Article 2 we examined whether generally well-developing children born very preterm differ in their gait characteristics (i.e., spatiotemporal and variability gait parameters) compared to full-term control children in single-task walking. Furthermore, we investigated whether concurrent tasks affect spatiotemporal as well as variability gait parameters of very preterm children. Finally, we examined whether concurrent tasks affect gait of very preterm children more strongly compared to controls. The sample of Article 2 consisted of 44 very preterm children (< 32 weeks of gestation, mean birth weight = 1,423 g) with a mean age

of 9.5 years ($SD = 1.3$) who were recruited from an initial cohort of 260 very preterm children, born between 2001 and 2006 and postnatally treated at the University Children's Hospital Basel (Switzerland). This sample of 44 very preterm children included 20 children with very low birth weight ($\leq 1,500$ g; mean birth weight: 1,026 g) and 24 children with birth weight $> 1,500$ g (mean birth weight: 1,754 g). The comparison sample included 44 full-term children (> 37 weeks of gestation) with a mean age of 9.5 years ($SD = 1.3$) who were recruited from birth announcements in newspapers as well as from local schools.

Article 3 (Manicolo⁺, Brotzmann⁺, Hagmann-von Arx, Grob, & Weber, *submitted*; ⁺shared first authorship). In Article 3 we examined whether children with ASD differ in gait characteristics (i.e., spatiotemporal and variability gait parameters) compared to typically developing controls in single-task walking. Furthermore, we investigated whether children with ASD and controls differ in their age of onset of independent walking and whether an association with gait variability exists. Additionally, in Article 3 we investigated whether children with ASD and control children differ in their motor skills and whether these skills are associated with gait variability. Finally, we examined whether gait variability of children with ASD shows an age-dependent decrease and converges toward that of control children. The sample of Article 3 consisted of 32 children with ASD with a mean age of 9.2 years ($SD = 3.8$) who were recruited from an initial cohort of 98 children diagnosed with ASD according to the ICD-10 (World Health Organization, 1992) and treated between 2008 and 2013 at the University Children's Hospital Basel (Switzerland). Children with Asperger's syndrome or pervasive developmental disorder not otherwise specified were not included in the study sample. For the control group, 36 typically developing siblings of participating children with ASD as well as children from private surroundings of coworkers were recruited (mean age: 9.0 years; $SD = 3.8$).

Article 4 (Manicolo, Grob, Lemola, & Hagmann-von Arx, 2016) and Article 5 (Manicolo, Grob, & Hagmann-von Arx, *submitted*). In Article 4 we examined whether

children with ADHD differ in their gait characteristics (i.e., spatiotemporal and variability gait parameters) compared to typically developing control children in single-task walking. Furthermore, in Article 4 we investigated whether gait variability of children with ADHD shows an age-dependent decrease and converges toward that of control children. In Article 5 we investigated whether a concurrent task affects gait of children with ADHD more strongly compared to controls and whether a motor concurrent task affects gait of children with ADHD more strongly than a cognitive concurrent task. The sample of Articles 4 and 5 consisted of 30 children diagnosed with ADHD with a mean age of 10.9 years ($SD = 1.5$) who were recruited from privately practicing pediatricians and the University Children's Hospital Basel (Switzerland). The inclusion criteria comprised an ADHD diagnosis according to DSM-IV (American Psychiatric Association, 1994) or ICD-10 (World Health Organization, 1992) and the diagnosis was confirmed by the Conners' Parent Rating Scale (Conners, 2001). Following recommendations by Thompson (2007), those children with ADHD who were being medicated discontinued medication at least 24 h before testing. A control group of 28 typically developing children with a mean age of 10.8 years ($SD = 1.4$) was recruited from local schools.

4.2 Measures

The measures and corresponding scales of each article are displayed in Table 1.

4.3 Procedure

The assessment of each child lasted approximately 1 to 3 h and consisted of different measures and corresponding scales depending on the study sample being investigated (see Table 1). However, gait analysis was performed with all children included in the present dissertation. The gait parameters were measured using GAITRite, which consists of a 701-cm-long walkway with 23,040 integrated pressure sensors and a 1.25-m-long nonrecordable zone on each end to minimize effects of acceleration and deceleration. Therefore, children walked approximately 10 m per walk and all gait analyses were performed according to the European guidelines for spatiotemporal analysis (Kressig, Beauchet, & European GAITRite Network

Group, 2006). For the sample of children with ASD and the corresponding control children, gait was investigated in single-task walking only, whereas for all other study samples (i.e., typically developing children, very preterm children, and children with ADHD, as well as corresponding control children) gait was further assessed while concurrently performing motor and cognitive tasks. The concurrent tasks were selected according to related and previously conducted research. All typically developing children included in Article 1 and all children with ADHD and control children included in Article 5 were asked to walk at their normal pace and simultaneously perform the cognitive task of listening to and memorize digits (i.e., digits task) and the motor task of fastening and unfastening a button at stomach height (i.e., button task) while walking. The concurrent digits and button tasks were also included in the investigation of children born very preterm and the corresponding control children included in Article 2. Additionally, two other concurrent tasks (one cognitive and one motor) were investigated: The cognitive concurrent task was naming animals at self-selected speed and rhythm and the motor concurrent task was carrying a tray (45 cm × 30 cm) loaded with seven table tennis balls. Hence, very preterm children and controls performed four dual-task walking conditions and, furthermore, their gait performance was assessed in three triple-task walking conditions. While triple-task walking, children were asked (1) to name animals and carry a tray with balls; (2) to listen to and memorize digits and carry a tray with balls; and (3) to listen to and memorize digits and fasten and unfasten a button.

Table 1

Description of measures and corresponding scales of each article

Article	Measure	Scale
Article 1	GAITRite	Spatiotemporal gait parameter: Velocity Variability gait parameters: CV stride velocity, CV stride time, CV stride length
	WISC-IV (Petermann & Petermann, 2011)	Intelligence (full-scale IQ)
	CANTAB	Executive functions
	Parents' report on children's motor behavior and injuries	Participation in sports, number of injuries
	IBC (Brandau & Daghofer, 2010)	Injury risk
	KIDSCREEN-52 (Ravens-Sieberer et al., 2008)	Psychosocial functioning
	M-ABC-2 (Petermann, 2008)	Motor skills, screening for DCD
Article 2	GAITRite	Spatiotemporal gait parameters: Velocity, cadence, stride length, single support time, double support time, normalized velocity, normalized cadence, normalized stride length Variability gait parameters: CV stride velocity, CV stride length
	WISC-IV (Petermann & Petermann, 2011)	Intelligence (full-scale IQ), screening for intellectual impairment
	M-ABC-2 (Petermann, 2008)	Motor skills, screening for DCD
	IDS (Grob, Meyer, & Hagmann-von Arx, 2009)	Subtest for selective attention
	SDQ (Goodman, 1997)	Hyperactivity-inattention
Article 3	GAITRite	Spatiotemporal gait parameters: Velocity, stride time, stride length, base of support Variability gait parameters: CV stride velocity, CV stride time, CV stride length
	Parents' reports on children's age of achievement of motor milestones	Sit upright autonomously, walk autonomously
	M-ABC-2 (Petermann, 2008)	Motor skills
Article 4	GAITRite	Spatiotemporal gait parameters: Velocity Variability gait parameters: CV stride length, CV stride time
	WISC-IV (Petermann & Petermann, 2011)	Intelligence (full-scale IQ), screening for intellectual impairment
	M-ABC-2 (Petermann, 2008)	Motor skills, screening for DCD
Article 5	GAITRite	Spatiotemporal gait parameters: Velocity, stride length, stride time Variability gait parameters: CV stride velocity, CV stride length, CV stride time
	WISC-IV (Petermann & Petermann, 2011)	Intelligence (full-scale IQ), screening for intellectual impairment
	M-ABC-2 (Petermann, 2008)	Motor skills, screening for DCD

Note. WISC-IV = Wechsler Intelligence Scale for Children, 4th edition. CANTAB = Cambridge Neuropsychological Test Automated Battery. IBC = Injury Behavior Checklist. M-ABC-2 = Movement Assessment Battery for Children, 2nd edition. IDS = Intelligence and Development Scales. SDQ = Strengths and Difficulties Questionnaire. CV = Coefficient of variation (%). DCD = Developmental coordination disorder.

5. Synopsis of Results

Chapter 5 summarizes the results of the articles included in the present dissertation according to the research questions.

5.1 Gait characteristics of typically developing children

Results of Article 1 (Hagmann-von Arx, Manicolo et al., 2016) for typically developing school-aged children revealed that in single-task walking, age was not related to gait velocity. However, when we accounted for differences in children's leg length and accordingly normalized gait velocity, results revealed a negative relation between age and normalized velocity, indicating that older children showed lower gait velocity than younger children. Further, a negative relation was found between age and gait variability, such that younger children walked with higher gait variability than older children. Regarding age-dependent dual-task effects on gait, the results revealed that in the motor dual-task condition where children had to fasten and unfasten a button while walking (i.e., button task), age was positively related to gait velocity, whereas no age-dependent dual-task effect on gait velocity was found in the cognitive dual-task condition where children were asked to listen to and memorize digits while walking (i.e., digits task). Additionally, in both dual-task conditions, age was negatively related to gait variability, such that younger children walked with higher gait variability than older children.

In dual-task conditions where children were asked to walk and simultaneously perform the concurrent digits or button task, children walked with reduced gait velocity and normalized gait velocity as well as increased gait variability compared to single-task walking. Furthermore, the motor concurrent task altered gait performance more strongly than the cognitive concurrent task, such that children showed a greater decrease in gait velocity and normalized velocity as well as greater increase in gait variability when walking and performing the button task compared to the digits task. Finally, in Article 1 no associations between the change in gait from single- to dual-task conditions (i.e., dual-task gait effects) and cognitive perfor-

mance, motor behavior, number of injuries, injury risk, or psychosocial functioning were revealed.

5.2 Gait characteristics of children born very preterm

For single-task walking, our results of Article 2 (Hagmann-von Arx et al., 2015) showed that generally well-developing school-aged children born very preterm did not differ in spatiotemporal and variability gait parameters compared to control children born full-term. Furthermore, dual- and triple-task conditions interfered with gait, leading to decreased gait velocity, cadence (steps per minute), and stride length as well as increased single support time (the time elapsed between the last contact of the current footfall and the initial contact of the next footfall of the same foot, expressed in seconds), double support time (the time when both feet are on the floor, expressed in seconds), and gait variability compared to single-task walking in both preterm and full-term children. The same pattern of results emerged for both groups of children for normalized gait parameters, showing lower normalized velocity, lower normalized cadence, and lower normalized stride length in dual- and triple-task conditions compared to single-task walking. Results additionally showed a systematic decrease in stride velocity variability from preterm children with birth weight $\leq 1,500$ g to preterm children with birth weight $> 1,500$ g to full-term children. This increase in stride velocity variability with decreasing maturity of the children at birth was most apparent in conditions in which the children had to listen to and memorize digits while walking. No significant group differences, however, emerged in spatiotemporal gait parameters, normalized gait parameters, or stride length variability.

5.3 Gait characteristics of children with ASD

Results of Article 3 (Manicolo, Brotzmann et al., *submitted*) showed that children with ASD walked with higher gait variability (i.e., higher variability for stride velocity, stride time, and stride length) and a wider base of support than controls. No group differences emerged

for gait velocity, stride time, or stride length, such that children with ASD did not show any significant alterations in these spatiotemporal gait parameters compared to controls.

Furthermore, in Article 3 we found that children from the control group were able to walk autonomously at an earlier age (i.e., mean age 13.3 months) than children with ASD (i.e., mean age 16.4 months). However, results further showed that this early motor milestone was not associated with the development of gait regularity of children with ASD and controls later in childhood, since there was no significant association of the age of onset of walking autonomously with any measure of later gait variability.

Results additionally revealed that compared to controls, children with ASD showed impaired motor skills, indicated by a lower overall score of the Movement Assessment Battery for Children, 2nd edition (M-ABC-2; Petermann, 2008) and lower scores in each of the areas examined by this test: manual dexterity, ball skills, and balance. For children with ASD, the M-ABC-2 overall score was negatively associated with gait variability, such that better motor skills went along with a more regular walking pattern (i.e., lower gait variability), whereas no such association was found for controls. Finally, results of Article 3 revealed that children with ASD displayed an age-dependent decrease in their gait variability toward that of typically developing control children.

5.4 Gait characteristics of children with ADHD

Article 4 (Manicolo et al., 2016) showed that in single-task walking, children with ADHD and control children had similar gait velocity and similar variability in stride length, whereas the two groups differed significantly in stride time variability, such that children with ADHD walked with higher variability than controls. Further, Article 4 also showed that age was negatively associated with gait variability in children with ADHD, indicating that with increasing age, gait became more regular and converged toward that of typically developing controls.

Results of Article 5 (Manicolo et al., *submitted*) showed that compared to single-task walking, dual tasking significantly affected walking performance of children with ADHD and typically developing controls (i.e., higher gait velocity, stride length, and gait variability as well as lower stride time), whereby dual-task effects on gait were comparable between the two groups. Finally, for children with ADHD and controls, the motor concurrent task affected gait performance more strongly than the cognitive concurrent task, such that children showed greater alterations in spatiotemporal and variability gait parameters when walking while performing the button task compared to the digits task.

6. General Discussion

The aim of the present dissertation was to expand current knowledge of gait characteristics in children with and without developmental risks and disorders by investigating spatio-temporal as well as variability gait parameters of typically developing children, children born very preterm, and children with ASD and ADHD when walking with and without concurrent tasks.

6.1 Gait characteristics of typically developing children

Results of Article 1 (Hagmann-von Arx, Manicolo et al., 2016) showed that while age was not related to gait velocity, a negative relation between age and normalized velocity as well as age and gait variability emerged. Hence, when we accounted for children's leg length, which was correlated with age and therefore may have confounded our results, older children walked with lower velocity than younger children. This finding contradicts previous results where normalized velocity was unaffected by age (Dusing & Thorpe, 2007). However, we normalized velocity to leg length (Hof, 1996), whereas Dusing and Thorpe (2007) normalized their data to height. Hence, because of the different methods of normalization, it is not possible to directly compare the results and draw conclusions. The negative relation between age and gait variability, on the other hand, is in line with previous research showing higher gait variability in younger compared to older typically developing children (Hausdorff et al., 1999). These results provide evidence that gait variability may be more sensitive to more subtle physiological changes such as neural maturation than spatiotemporal gait parameters (Hausdorff, 2005) and that gait variability continues to develop into adolescence. At the same time, our results highlight the importance of not only assessing spatiotemporal gait parameters but also considering gait variability as an index of gait automaticity and regularity when investigating typically developing children's gait maturation, because these gait measures seem to undergo temporally distinct developmental trajectories.

Compared to single-task walking, dual-task conditions caused children to walk with reduced gait velocity and normalized gait velocity as well as increased gait variability, which is in accordance with previous research (Boonyong et al., 2012; Cherng et al., 2007; Hung et al., 2013). Hence, our results further support the notion that also for children, gait is not a fully automatic activity but rather requires cognitive processes such as executive functions (e.g., Woollacott & Shumway-Cook, 2002). Furthermore, our results concerning age-dependent dual-task effects confirm previous findings (Boonyong et al., 2012) by showing that younger children walked with lower gait velocity than older children when walking and concurrently fastening and unfastening a button. Accordingly, we found that younger children walked with higher gait variability than older children in both dual-task conditions (i.e., digits and button task), confirming that dual-task gait is still developing in middle childhood (Abbruzzese et al., 2014).

We were further able to show that dual-task effects on walking differed between the two types of concurrent tasks, with the motor concurrent task (i.e., button task) causing greater gait alterations in spatiotemporal and variability parameters than the cognitive concurrent task (i.e., digits task). These findings can be interpreted from the perspective of the multiple-resource model of attention (Wickens, 1991) that assumes that two tasks will interfere with each other if they share the same pool of resources. Walking requires visual input and further involves the response of moving and controlling body segments, which can be subsumed under the term somatosensation (cf. Cherng et al., 2007). The motor concurrent button task also requires visual input as well as a somatosensory response. In contrast, the cognitive concurrent digits task requires auditory input and involves a vocal response. According to these assumptions, the button task competes more strongly for processing resources with walking (i.e., visual input and somatosensory response) than the digits task, which may explain why greater dual-task gait decrements were found for the motor compared to the cognitive dual-task walking condition.

Finally, our results revealed that no association between the change in gait from single- to dual-task conditions (i.e., dual-task gait effects) and cognition as well as other aspects of children's development (e.g., motor behavior, number of injuries) exists. Since we were the first to investigate such associations in a sample of typically developing children, our results provide preliminary evidence that dual-task gait effects are not related to these aforementioned aspects of child development during middle childhood. However, the dual-task gait decrements apparent in Article 1 (Hagmann-von Arx, Manicolo et al., 2016) support the notion that also among typically developing children, cognitive processes play an important role in gait control.

6.2 Gait characteristics of children born very preterm

Our results reported in Article 2 (Hagmann-von Arx et al., 2015) showed that concurrent task performance while walking altered spatiotemporal and variability gait parameters of children born very preterm and control children born full-term, thus further supporting the notion that gait requires cognitive processes such as executive functions (Woollacott & Shumway-Cook, 2002). Furthermore, while in single-task walking children born very preterm did not differ in spatiotemporal and variability gait parameters compared to controls, concurrent task performance in dual- and triple-task conditions revealed group differences in stride velocity variability, with a systematic decrease in stride velocity variability from preterm children with birth weight $\leq 1,500$ g to preterm children with birth weight $> 1,500$ g to full-term children. These findings are in line with research showing that motor impairments occur more frequently in preterm children who were less mature at birth (De Kieviet et al., 2009; Erikson, Allert, Carlberg, & Katz-Salamon, 2003). Furthermore, higher gait variability is also present in individuals who exhibit impairments in executive functions (e.g., Hausdorff, 2005; Sheridan et al., 2003; Yogev et al., 2005; Yogev-Seligmann et al., 2008), suggesting that deficits in executive functions in preterm children (Aarnoudse-Moens et al., 2009; Hagmann-von Arx et al., 2014; Mulder et al., 2009) may have contributed to higher stride velocity variability when

comparing the group of preterm children to controls reported in Article 2 (Hagmann-von Arx et al., 2015). Further, the systematic increase in stride velocity variability with decreasing maturity of the children at birth was most apparent in conditions in which children had to listen to and memorize digits. This finding is consistent with a previous study reporting that a concurrent auditory task showed the largest interference effect on gait in typically developing children (Huang, Mercer, & Thorpe, 2003), suggesting that walking while performing a task requiring continuous processing of new auditory information is particularly difficult. Since no group differences, however, emerged for spatiotemporal and normalized gait parameters, our results further support the notion that gait variability may provide a more discriminant and sensitive measure of gait than other gait variables (Hausdorff, 2005).

6.3 Gait characteristics of children with ASD

In accordance with previous studies (Nayate et al., 2012; Rinehart, Tonge, Bradshaw, et al., 2006; Rinehart, Tonge, Iansek, et al., 2006), we found in Article 3 (Manicolo, Brotzmann et al., *submitted*) that children with ASD walked with higher gait variability along with a wider base of support, indicating a less regular and less steady walking pattern than typically developing controls (Nobile et al., 2010; Shetreat-Klein, Shinnar, & Rapin, 2012). Furthermore, our results showed no group differences in gait velocity, stride time, or stride length and, therefore, confirmed previous findings reporting no significant alterations in these spatiotemporal gait parameters in children with ASD compared to controls (Rinehart, Tonge, Bradshaw, et al., 2006; Rinehart, Tonge, Iansek, et al., 2006). Hence, as mentioned above for very preterm children, the here-reported findings for children with ASD highlight the importance of investigating gait variability, providing a discriminant and sensitive measure of gait performance (Hausdorff, 2005).

In line with results of previous studies (Ozonoff et al., 2008; Provost et al., 2007; Segawa & Nomura, 1991; Teitelbaum, Teitelbaum, Nye, Fryman, & Maurer, 1998), our data from parents' reports showed that children from the ASD group reached the motor milestone

of walking autonomously later (i.e., mean age 16.4 months) than controls (i.e., mean age 13.3 months). However, results for children with and without ASD further showed that this early motor milestone was not associated with later gait regularity. As we were the first to investigate such associations, our findings provide preliminary evidence to refute the assumption that the age of reaching the motor milestone of walking autonomously during infancy will predict later gait development during childhood among subjects with ASD. Nevertheless, the information on early motor milestones is based on retrospective parental reports and hence needs to be interpreted with caution.

Our results additionally revealed that children with ASD not only showed significant difficulties with motor skills, indicated by a lower M-ABC-2 overall score as well as lower skills in each area examined by this test (i.e., manual dexterity, ball skills, balance), but also that among children with ASD, better motor skills went along with a more regular walking pattern, indicated by lower gait variability, whereas no such association was found for controls. Hence, while our findings on impaired motor skills in children with ASD replicate previous findings (e.g., Green et al., 2002, 2009; Hilton et al., 2007; Liu & Breslin, 2013), our results are the first to show that those impairments in motor skills are associated with gait regularity in children with ASD. Thus, gait regularity may form a further dimension of motor dysfunction associated with ASD (Paquet et al., 2015) and may be part of a more general impairment in movement ranging from fine and gross motor skills measured by the M-ABC-2 to the planning and execution of skilled motor sequences such as walking (Minschew, Sung, Jones & Furman, 2004).

Finally, we were the first to show that gait variability of children with ASD displayed an age-dependent decrease toward that of controls, indicating that their gait performance becomes more regular with increasing age and converges toward that of typically developing controls. A possible explanation for this result may lie in the reported delay in brain maturation in prefrontal brain structures of children with ASD (Zilbovicius et al., 1995), which,

among other things, include higher order motor control regions (Shaw et al., 2007, 2012). However, the cerebellum, which is significantly involved in motor movement and locomotor activity (e.g., Anderson, Polcari, Lowen, Renshaw, & Teicher, 20014; Pasini, D'Agati, Pitzianti, Casarelli, & Curatolo, 2012), may also have played a role in our finding of a developmental delay in gait regularity among children with ASD, since previous studies reported abnormalities such as volume reduction in children with ASD (Dougherty, Evans, Myers, Moore, & Michael, 2015). Still, these explanations regarding neural underpinnings are only assumptions because we were not able to directly investigate a possible association between brain maturation, structural abnormalities, and gait patterns in children with ASD.

6.4 Gait characteristics of children with ADHD

In accordance with previous research, results of Article 4 (Manicolo et al., 2016) indicate that compared to controls, children with ADHD showed similar gait velocity and similar stride length variability but significantly higher variability in stride time in single-task walking. These results lend support to the notion of a less regular gait pattern in children with ADHD compared to typically developing children (Leitner et al., 2007; Papadopoulos et al., 2014) and at the same time highlight once more the importance of including gait variability as a sensitive and discriminant measure in gait assessment (Hausdorff, 2005). Given that gait variability has been linked to executive functions in adult samples (Amboni et al., 2013), deficits in executive functions associated with ADHD (Willcutt et al., 2005) may have contributed to the alterations in gait variability among children with ADHD reported in this dissertation. However, deeper brain structures such as the basal ganglia and the cerebellar vermis are also known to be involved in the regulation of locomotor activity (Engström, Van't Hooft, & Tedroff, 2012), often referred to as “motor control” (Leitner et al., 2007). Thus, the alterations in gait variability reported here might be related not only to executive functions associated with frontal brain regions (Silk et al., 2005) but also to subcortical motor structures.

Furthermore, our results showed that children with ADHD displayed an age-dependent decrease in their gait variability and therefore an increase in gait regularity toward that of controls. This may indicate that children with ADHD lag behind in their gait development compared to typically developing children but eventually approach normality with increasing age (Burke & Edge, 2013). Further support for this assumption stems from neurodevelopmental findings showing that children with ADHD display a delay in brain maturation—particularly in prefrontal regions important for cognitive processes, including executive functions, and also for motor planning—but that brain maturation eventually converges toward typically developing controls (Shaw et al., 2007). Therefore, one could hypothesize that this maturational delay in prefrontal regions may be associated with the here-reported maturational process in gait regularity in children with ADHD. However, as mentioned above regarding possible neural underpinnings of gait alterations in children with ASD, we explored neither potential underlying mechanisms nor the origins of the neural control related to gait variability and its possible association with brain maturation in children with ADHD.

Additionally, in Article 5 (Manicolo et al., *submitted*) we found that dual-task effects on gait are apparent for a cognitive and a motor concurrent task: When listening to and memorizing digits and when unfastening and fastening a button while walking, both children with ADHD and typically developing controls showed a decrease in gait velocity and stride length whereas stride time and all measures of gait variability increased compared to single-task walking. For children with ADHD our results are therefore the first to show that not only a cognitive concurrent task (Leitner et al., 2007) but also a motor concurrent task affects gait performance. Further, our results are in line with previous research showing that in typically developing children, cognitive (Boonyong et al., 2012; Huang et al., 2003) and motor (Cherng et al., 2007; Hung et al., 2013) concurrent tasks affect gait. Hence, as mentioned above for very preterm children (i.e., Article 2; Hagmann-von Arx et al., 2015) as well as for typically developing children (i.e., Article 1; Hagmann-von Arx, Manicolo et al., 2016), the results

showing dual-task gait effects in children with ADHD and controls further support the notion that gait is not a fully automatic activity but rather requires cognitive processes (Woollacott & Shumway-Cook, 2002). At the same time, our results show that children with ADHD and controls did not differ in any gait parameter in both dual-task conditions. This is in contrast to our hypothesis included in Article 5 (Manicolo et al., *submitted*) stating that children with ADHD will show more strongly compromised dual-task gait performance compared to children without ADHD. Since impaired executive functions are common for children with ADHD (e.g., Gillberg, 2003; Steger et al., 2001; Wilding, 2005; Willcutt et al., 2005), these results may to some extent contradict previous findings reporting a link between impaired executive functions and poorer gait performance in dual-task conditions among healthy older adults compared to healthy young adults (Beurskens & Bock, 2012) and among clinical adult samples compared to healthy controls (Sheridan et al., 2003; Yogev et al., 2005). However, our results are in line with Leitner et al. (2007) reporting that the effect of dual tasking on gait was comparable between children with and without ADHD.

Finally, in line with the findings mentioned above for Article 1 (Hagmann-von Arx, Manicolo et al., 2016) with typically developing children, our results showed that dual-task effects on walking differed between the two types of concurrent tasks: For children with ADHD as well as for controls, the motor concurrent button task caused a greater decrease in spatiotemporal gait parameters and a greater increase in gait variability than the cognitive concurrent digits task. Therefore, this finding is in line with previous research indicating a greater dual-task gait effect for a motor than for a cognitive concurrent task (Cherng et al., 2007) and can also be interpreted from the perspective of the multiple-resource model of attention that assumes two tasks will interfere with each other if they share the same pool of resources (Wickens, 1991). Hence, not only for typically developing controls but also for children with ADHD, the motor concurrent button task possibly interfered more strongly with

walking regarding processing resources and therefore caused a greater dual-task gait effect than the cognitive concurrent digits task.

6.5 Strengths and Limitations

An important strength of the present dissertation is the inclusion of different study samples, offering the opportunity to investigate gait characteristics of children following typical development as well as further focus on gait characteristics of children with a developmental disorder such as ASD and ADHD or a developmental risk factor such as preterm birth. In this vein, the present dissertation addresses a broad range of important research questions related to gait development and therefore extends the still limited knowledge on gait characteristics of clinical and nonclinical child samples. At the same time, we were able to recruit large study samples covering a wide age range. Especially for the samples of children with a developmental risk or a developmental disorder we were able to investigate larger numbers of children than in previous studies.

A further strength is the inclusion of homogenous cohorts of children in the clinical samples. Given that previous studies indicated differences between children with Asperger's syndrome and children with infantile or atypical autism in their neurological basis, clinical characteristics, and comorbidities (Remscheid & Kamp-Becker, 2007) as well as differences in motor performance (Papadopoulos et al., 2012) including gait patterns (e.g., Rinehart, Tonge, Bradshaw, et al., 2006), we included only children with infantile and atypical autism and excluded children with Asperger's syndrome or pervasive developmental disorder not otherwise specified from our study sample. Furthermore, typically developing children, including all control children, as well as children with ADHD and very preterm children were screened for developmental coordination disorder and were excluded from the study sample if significant motor impairment was indicated by an M-ABC-2 overall score below the 16th percentile (Petermann, 2008).

Another strength of the present dissertation is that gait characteristics were assessed using the electronic GAITRite system, which has proved to be a valid and objective method for measuring gait parameters in children and offers the possibility of reliably identifying subtle changes in gait (Thorpe et al., 2005). Furthermore, during gait assessment children wore their normal clothes and shoes and it was therefore possible to assess gait performance as it is exhibited under daily circumstances.

Although the present dissertation has a number of strengths and is able to provide important knowledge related to gait characteristics in children with and without developmental risks and disorders, it also has its limitations. Regarding gait assessment, the walkway system GAITRite allowed us to analyze spatiotemporal gait parameters and to calculate variability measures thereof. However, GAITRite allows neither the investigation of peculiar walking patterns such as toe walking, which has previously been reported for children with ASD (Accardo & Barrow, 2015; Barrow, Jaworski, & Accardo, 2011; Marcus, Sinnott, Bradley, & Grey, 2010) and children with ADHD (Engström et al., 2012), nor the qualitative analysis of gait motion, such as head and trunk posturing (Rinehart, Tonge, Bradshaw, et al., 2006) or kinetic gait parameters (Chester, Tingley, & Biden, 2006).

A further limitation is that our analyses were performed on cross-sectional data. However, the testing of developmental trends and changes as well as maturational patterns in single- and dual-task walking should be based on longitudinal data, ideally including the objective assessment of infant prewalking motor milestones.

As mentioned above, along with typically developing children and children from the preterm sample, participating children with ADHD were screened for developmental coordination disorder to make sure that none had significant motor impairments, which could have interfered with their gait performance. However, up to 47% of children with ADHD and up to 41% of preterm children meet diagnostic criteria for developmental coordination disorder (Edwards et al., 2011; Kadesjö & Gillberg, 2003; Martin, Piek, Baynam, Levy, & Hay, 2010;

Tervo, Azuma, Fogas, & Fiechtner, 2002; Williams, Lee, & Anderson, 2010) and hence our results cannot be generalized to individuals with a co-morbid diagnosis. Additionally, children with ADHD were not classified according to any ADHD subtype and we were therefore not able to investigate whether gait characteristics differ between subtypes.

Finally, our sample of children with ASD included children being medicated as well as children without medication. However, because of the small number of children being medicated (i.e., nine children), we could not investigate possible medication effects and our findings therefore cannot be generalized to drug-naïve subjects with ASD.

6.6 Conclusions and Outlook

Taken together, the results of the present dissertation indicate that gait forms an important part of children's motor functioning and undergoes significant developmental changes across childhood. In this vein, findings from Article 1 (Hagmann-von Arx, Manicolo et al., 2016), Article 3 (Manicolo, Brotzmann et al., *submitted*), and Article 4 (Manicolo et al., 2016) with typically developing children and children with ASD and ADHD showed age-dependent gait alterations, indicating that gait is still developing during middle childhood. Furthermore, when compared to typically developing controls, both children with ASD and children with ADHD displayed a delay in gait development, indicated by a higher gait variability, which decreased with increasing age toward that of controls. Hence, this similarity in the developmental pattern of gait variability found for children with ASD and ADHD in the present dissertation may add to the growing body of research highlighting common behavioral, cognitive, and neural features of these two neurodevelopmental disorders, including a delay in brain maturation in prefrontal structures (Dougherty et al., 2015; Shaw et al., 2007, 2012; Zilbovicius et al., 1995). However, it remains the task of future research to shed further light on possible common neural underpinnings of the here-reported gait alterations and age-dependent decrease in gait variability among subjects with ASD and ADHD. Additionally, future studies investigating children's gait development should apply a longitudinal approach as

well as include a comparison sample of adult participants in order to determine at what age subjects reach maturity in different gait parameters.

When comparing gait characteristics of typically developing children with those of children with a developmental risk factor (Article 2; Hagmann-von Arx et al., 2015) or a developmental disorder (Article 3; Manicolo, Brotzmann et al., *submitted*; Article 4; Manicolo et al., 2016; Article 5; Manicolo et al., *submitted*), we found significant group differences for gait parameters in either single-task walking or when children were asked to perform concurrent tasks while walking. Hence, our findings support the inclusion of gait analysis when investigating children's motor functioning and endorse a shift in focus to a movement perspective, which may provide new insight on children's motor development (Kindregan et al., 2015; Provost et al., 2007). Particularly regarding developmental disorders such as ADHD or ASD for which deviations from normative motor development are not included as primary diagnostic categories (American Psychiatric Association, 2013), the findings of the present dissertation support the importance of considering motor functioning, including gait parameters, in addition to other developmental skill areas outlined in diagnostic manuals. However, since the number of studies including quantitative methods for gait analysis of children with and without developmental risks and disorders is still very limited, the findings reported here need replication. Future studies should attempt not only to replicate but also to extend our findings by investigating in an integrative approach various aspects of children's locomotion such as spatiotemporal and variability gait measures along with qualitative measures such as head and trunk posturing (Rinehart, Tonge, Bradshaw, et al., 2006) as well as kinetic and kinematic gait parameters (Chester et al., 2006). This approach may prospectively help with determining the degree of specificity of deficits and the development of useful tools for diagnosis (Kindregan et al., 2015; Provost et al., 2007).

Regarding gait parameters, findings of all five articles included in the present dissertation showed that age-dependent effects as well as group differences between children with

and without a developmental risk factor or a developmental disorder are most apparent in variability measures of gait (cf. Article 1; Hagmann-von Arx, Manicolo et al., 2016; Article 2; Hagmann-von Arx et al., 2015; Article 3; Manicolo, Brotzmann et al., *submitted*; Article 4; Manicolo et al., 2016; Article 5; Manicolo et al., *submitted*). Hence, in addition to being a more discriminant gait measure than spatiotemporal parameters, gait variability also undergoes a temporally distinct developmental trajectory (Hausdorff, 2005). Following previous research with adult samples, it has been suggested that gait variability reflects the underlying neural control of gait, with demonstrated sensitivity to pathological and aging processes (e.g., Lord, Howe, Greenland, Simpson, & Rochester, 2011). However, for child samples, gait variability has not been studied as extensively and findings of the present dissertation may therefore underscore the importance for future studies to include measures of gait variability when investigating walking characteristics as well as when quantifying gait maturity of clinical and nonclinical samples.

With regard to walking and concurrently performing tasks, Article 1 (Hagmann-von Arx, Manicolo et al., 2016), Article 2 (Hagmann-von Arx et al., 2015), and Article 5 (Manicolo et al., *submitted*) with typically developing children, very preterm children, and children with ADHD consistently found that children's gait parameters show alterations when children engage in concurrent tasks compared to single-task walking. These results support the suggestion that walking is not a fully automatic activity but rather requires cognitive processes (e.g., Woollacott & Shumway-Cook, 2002). As mentioned earlier (cf., Chapter 2, Section 2.4), two theories have been proposed to explain gait alterations while performing a concurrent task, namely, the capacity-sharing theory (Kahneman, 1973; Tombu & Jolicœur, 2003) and the bottleneck theory (Pashler, 1994). However, our findings do not favor one theory over the other and it therefore remains the task of future research to investigate underlying mechanisms of dual-task interference and clarify which theory best explains cognitive processing and dual-task effects (Yogev-Seligmann et al., 2008).

Additionally, findings of Article 1 (Hagmann-von Arx, Manicolo et al., 2016) and Article 5 (Manicolo et al., *submitted*) showed that a motor concurrent task affected gait performance of typically developing children and children with ADHD more strongly than a cognitive concurrent task. We interpreted these findings following the multiple-resource model of attention (Wickens, 1991) and accordingly assumed that the motor concurrent task competes more strongly for processing resources with walking and therefore caused greater dual-task gait decrements than the cognitive concurrent task. Thus, for future studies results of the present dissertation underscore the importance of taking the type of concurrent task into account when investigating children's gait in a dual-task paradigm. Additionally, Article 2 (Hagmann-von Arx et al., 2015) with very preterm children showed that with decreasing maturity of the children, gait variability increased, which was most apparent in conditions in which children had to listen to and memorize digits. Hence, different types of concurrent tasks may affect gait differently and future research could therefore systematically investigate other types of concurrent tasks and compare their effects on children's gait parameters. Knowing the effects concurrent tasks may have on the walking performance of children may raise the awareness of how activities should be structured to minimize dual-task interference and therefore possibly prevent accidental injuries.

In sum, the findings of the present dissertation extend existing research on gait of typically developing children and children with developmental risks and disorders by providing information on their walking characteristics in single- and dual-task conditions. At the same time, our findings support the idea that cognitive processes are involved in the control of gait and highlight the necessity to account for children's age, the type of concurrent task, and the careful selection and interpretation of the gait parameters under consideration.

References

- Aarnoudse-Moens, C. S. H., Weisglas-Kuperus, N., van Goudoever, J. B., & Oosterlaan, J. (2009). Meta-analysis of neurobehavioral outcomes in very preterm and/or very low birth weight children. *Pediatrics*, *124*, 717–728.
- Abbruzzese, L. D., Ashwini, R. K., Bellows, R., Figueroa, K., Levy, J., Lim, E., & Puccio, L. (2014). Effects of manual task complexity on gait parameters in school-aged children and adults. *Gait and Posture*, *40*, 658–663.
- Accardo, P. J., & Barrow, W. (2015). Toe walking in autism: Further observations. *Journal of Child Neurology*, *30*, 606–609.
- Adolph, K. E., Vereijken, B., & Shrout, P. E. (2003). What changes in infant walking and why. *Child Development*, *74*, 475–497.
- Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., & Cockburn, J. (2011). Cognitive motor interference while walking: A systematic review and meta-analysis. *Neuroscience & Biobehavioral Reviews*, *35*, 715–728.
- Amboni, M., Barone, P., & Hausdorff, J. M. (2013). Cognitive contributions to gait and falls: Evidence and implications. *Movement Disorders*, *28*, 1520–1533.
- American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: American Psychiatric Press.
- American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.
- Anderson, C. M., Polcari, A., Lowen, S. B., Renshaw, P. F., & Teicher, M. H. (2014). Effects of methylphenidate on functional magnetic resonance relaxometry of the cerebellar vermis in boys with ADHD. *American Journal of Psychiatry*, *159*, 1322–1328.
- Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology*, *8*, 71–82.

- Barrow, W., Jaworski, M., & Accardo, P. J. (2011). Persistent toe walking in autism. *Journal of Child Neurology*, 26, 619–621.
- Beauchet, O., Annweiler, C., Dubost, V., Allali, G., Kressig, R. W., Bridenbaugh, S., ... Herrmann, F. R. (2009). Stops walking when talking: A predictor of falls in older adults? *European Journal of Neurology*, 16, 786–795.
- Bejerot, S., Plenty, S., Humble, A., & Humble, M. B. (2013). Poor motor skills: A risk marker for bully victimization. *Aggressive Behavior*, 39, 453–461.
- Beurskens, R., & Bock, O. (2012). Age-related deficits of dual-task walking: A review. *Neural Plasticity*, 2012.
- Bilney, B., Morris, M., & Webster, K. (2003). Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. *Gait and Posture*, 17, 68–74.
- Bloemers, F., Collard, D., Paw, M. C. A., Van Mechelen, W., Twisk, J., & Verhagen, E. (2011). Physical inactivity is a risk factor for physical activity-related injuries in children. *British Journal of Sports Medicine*, 46, 669–674.
- Boonyong, S., Siu, K. C., van Donkelaar, P., Chou, L. S., & Woollacott, M. H. (2012). Development of postural control during gait in typically developing children: The effects of dual-task conditions. *Gait and Posture*, 35, 428–434.
- Brandau, H., & Daghofer, F. (2010). Elternfragebogen zur Erfassung des Unfallrisikos von Jungen [Parental questionnaire for injury risk assessment of young boys]. *Diagnostica*, 56, 33–45.
- Bridenbaugh, S. A. & Kressig, R. W. (2010). Laboratory review: The role of gait analysis in seniors' mobility and fall prevention. *Gerontology*, 57, 256–264.
- Bruijn, S. M., Meijer, O. G., Beek, P. J., & Van Dieën, J. H. (2013). Assessing the stability of human locomotion: a review of current measures. *Journal of the Royal Society Interface*, 10, 20120999.

- Burke, A., & Edge, A. (2013). Neurodevelopmental pathways of childhood ADHD into adulthood: Maturational lag, deviation, or both? In S. Banerjee (Ed.), *Attention deficit hyperactivity disorder in children and adolescents*. InTech, doi: 10.5772/53865.
- Cairney, J., Hay, J. A., Fought, B. E., Wade, T. J., Corna, L., & Flouris, S. (2005). Developmental coordination disorder, generalized self-efficacy toward physical activity, and participation in organized and free play activities. *The Journal of Pediatrics*, 147, 515–520.
- Cherng, R. J., Liang, L. Y., Chen, Y. J., & Chen, J. Y. (2009). The effects of a motor and a cognitive concurrent task on walking in children with developmental coordination disorder. *Gait and Posture*, 29, 204–207.
- Cherng, R. J., Liang, L. Y., Hwang, I. S., & Chen, J. Y. (2007). The effect of a concurrent task on the walking performance of preschool children. *Gait and Posture*, 26, 231–237.
- Chester, V. L., & Calhoun, M. (2012). Gait symmetry in children with autism. *Autism Research and Treatment*, 2012.
- Chester, V. L., Tingley, M., & Biden, E. N. (2006). A comparison of kinetic gait parameters for 3–13 year olds. *Clinical Biomechanics*, 21, 726–732.
- Conners, C. K. (2001). *Conners' rating scales-revised: Technical manual*. North Tonawanda, NY: Multi-Health Systems.
- Cutlip, R. G., Mancinelli, C., Huber, F., & DiPasquale, J. (2000). Evaluation of an instrumented walkway for measurement of the kinematic parameters of gait. *Gait and Posture*, 12, 134–138.
- De Kieviet, J. F., Piek, J. P., Aarnoudse-Moens, C. S., & Oosterlaan, J. (2009). Motor development in very preterm and very low-birth-weight children from birth to adolescence: A meta-analysis. *JAMA*, 302, 2235–2242.

- Dougherty, C. C., Evans, D. W., Myers, S. M., Moore, G. J., & Michael, A. M. (2015). A comparison of structural brain imaging findings in autism spectrum disorder and attention-deficit hyperactivity disorder. *Neuropsychology Review*. Advance online publication.
- Drillis, R. (1958). Objective recording and biomechanics of pathological gait. *Annals of the New York Academy of Sciences*, 74, 86–109.
- Dusing, S. C., & Thorpe, D. E. (2007). A normative sample of temporal and spatial gait parameters in children using the GAITRite electronic walkway. *Gait and Posture* 25, 135–139.
- Eaves, L. C., & Ho, H. H. (2008). Young adult outcome of autism spectrum disorders. *Journal of Autism and Developmental Disorders*, 38, 739–747.
- Edwards, J., Berube, M., Erlandson, K., Haug, S., Johnstone, H., Meagher, M., ... Zwicker, J. G. (2011). Developmental coordination disorder in school-aged children born very preterm and/or at very low birth weight: A systematic review. *Journal of Developmental & Behavioral Pediatrics*, 32, 678–687.
- Engström, P., Van't Hooft, I., & Tedroff, K. (2012). Neuropsychiatric symptoms and problems among children with idiopathic toe-walking. *Journal of Pediatric Orthopaedics*, 32, 848–852.
- Erikson, C., Allert, C., Carlberg, E. B., & Katz-Salamon, M. (2003). Stability of longitudinal motor development in very low birthweight infants from 5 months to 5.5 years. *Acta Paediatrica*, 92, 197–203.
- Faraone, S. V., Biederman, J., & Mick, E. (2006). The age-dependent decline of attention deficit hyperactivity disorder: A meta-analysis of follow-up studies. *Psychological Medicine*, 36, 159–165.

- Fein, D., Barton, M., Eigsti, I. M., Kelley, E., Naigles, L., Schultz, R. T., ... Troyb, E. (2013). Optimal outcome in individuals with a history of autism. *Journal of Child Psychology and Psychiatry*, 54, 195–205.
- Fischer, M., & Barkley, R. A. (2007). The persistence of ADHD into adulthood: (Once again) it depends on whom you ask. *The ADHD Report*, 15, 7–16.
- Froehle, A. W., Nahhas, R. W., Sherwood, R. J., & Duren, D. L. (2013). Age-related changes in spatiotemporal characteristics of gait accompany ongoing lower limb linear growth in late childhood and early adolescence. *Gait and Posture*, 38, 14–19.
- Gabell, A., & Nayak, U. S. (1984). The effect of age on variability in gait. *Journal of Gerontology*, 39, 662–666.
- Gabriel, M., Pallás Alonso, C. R., De La Cruz Bértolo, J., Caserío Carbonero, S., López Maestro, M., Moral Pumarega, M., ... Lora Pablos, D. (2009). Age of sitting unsupported and independent walking in very low birth weight preterm infants with normal motor development at 2 years. *Acta Paediatrica*, 98, 1815–1821.
- Gillberg, C. (2003). Deficits in attention, motor control, and perception: A brief review. *Archives of Disease in Childhood*, 88, 904–910.
- Goodman, R. (1997). The strengths and difficulties questionnaire: A research note. *Journal of Child Psychology and Psychiatry*, 38, 581–586.
- Goyen, T. A., & Lui, K. (2009). Developmental coordination disorder in “apparently normal” schoolchildren born extremely preterm. *Archives of Disease in Childhood*, 94, 298–302.
- Green, D., Baird, G., Barnett, A. L., Henderson, L., Huber, J., & Henderson, S. E. (2002). The severity and nature of motor impairment in Asperger’s syndrome: A comparison with specific developmental disorder of motor function. *Journal of Child Psychology and Psychiatry*, 43, 655–668.

- Green D., Charman T., Pickles, A., Chandler, S., Loucas, T., Simonoff, E., & Baird, G. (2009). Impairment in movement skills of children with autistic spectrum disorders. *Developmental Medicine and Child Neurology*, 51, 311–316.
- Grob, A., Meyer, C. S., & Hagmann-von Arx, P. (2009). *Intelligence and Development Scales*. Bern, Switzerland: Hans Huber.
- Hagmann-von Arx, P., Perkinson-Gloor, N., Brand, S., Albert, D., Holsboer-Trachsler, E., Grob, A., ... Lemola, S. (2014). In school-age children who were born very preterm sleep efficiency is associated with cognitive function. *Neuropsychobiology*, 70, 244–252.
- Hausdorff, J. M. (2005). Gait variability: Methods, modeling and meaning. *Journal of Neuroengineering and Rehabilitation*, 2.
- Hausdorff, J. M. (2007). Gait dynamics, fractals and falls: Finding meaning in the stride-to-stride fluctuations of human walking. *Human Movement Science*, 26, 555–589.
- Hausdorff, J. M., Zemani, L., Peng, C.-K., & Goldberger, A. L. (1999). Maturation of gait dynamics: Stride-to-stride variability and its temporal organization in children. *Journal of Applied Physiology*, 86, 1040–1047.
- Hillman, S. J., Stansfield, B. W., Richardson, A. M., & Robb, J. E. (2009). Development of temporal and distance parameters of gait in normal children. *Gait and Posture*, 29, 81–85.
- Hilton, C., Wente, L., LaVesser, P., Ito, M., Reed, C., & Herzberg, G. (2007). Relationship between motor skill impairment and severity in children with Asperger syndrome. *Research in Autism Spectrum Disorders*, 1, 339–349.
- Hof, A. L. (1996). Scaling gait data to body size. *Gait and Posture*, 4, 222–223.
- Holm, I., Tveter, A. T., Fredriksen, P. M., & Vollestad, N. (2009). A normative sample of gait and hopping on one leg parameters in children 7-12 years of age. *Gait and Posture*, 27, 91–96.

- Huang, H. J., & Mercer, V. S. (2001). Dual-task methodology: Applications in studies of cognitive and motor performance in adults and children. *Pediatric Physical Therapy*, 13, 133–140.
- Huang, H. J., Mercer, V. S., & Thorpe, D. E. (2003). Effects of different concurrent cognitive tasks on temporal-distance gait variables in children. *Pediatric Physical Therapy*, 15, 105–113.
- Hung, Y. C., Meredith, G. S., & Gill, S. V. (2013). Influence of dual task constraints during walking for children. *Gait and Posture*, 38, 450–454.
- Jeng, S. F., Chen, L. C., Tsou, K. I., Chen, W. J., & Luo, H. J. (2004). Relationship between spontaneous kicking and age of walking attainment in preterm infants with very low birth weight and full-term infants. *Physical Therapy*, 84, 159–172.
- Jeng, S. F., Lau, T. W., Hsieh, W. S., Luo, H. J., Chen, P. S., Lin, K. H., & Shieh, J. Y. (2008). Development of walking in preterm and term infants: Age of onset, qualitative features and sensitivity to resonance. *Gait and Posture*, 27, 340–346.
- Jeng, S. F., Yau, K. I. T., Liao, H. F., Chen, L. C., & Chen, P. S. (2000). Prognostic factors for walking attainment in very low-birthweight preterm infants. *Early Human Development*, 59, 159–173.
- Kadesjö, B., & Gillberg, C. (2003). The comorbidity of ADHD in the general population of Swedish school-age children. *Journal of Child Psychology and Psychiatry*, 42, 487–492.
- Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice Hall.
- Katz-Leurer, M., Rotem, H., Keren, O., & Meyer, S. (2011). Effect of concurrent cognitive tasks on gait features among children post-severe traumatic brain injury and typically-developed controls. *Brain Injury*, 25, 581–586.

- Katz-Leurer, M., Rotem, H., & Meyer, S. (2013). Effects of concurrent cognitive tasks on temporo-spatial parameters of gait among children with cerebral palsy and typically developed controls. *Developmental Neurorehabilitation*, 17, 363–367.
- Keen, M. (1993). Early development and attainment of normal mature gait. *Journal of Prosthetics and Orthotics*, 5, 35–39.
- Kindregan, D., Gallagher, L., & Gormley, J. (2015). Gait deviations in children with autism spectrum disorders: A review. *Autism Research and Treatment*, 2015.
- Kressig, R. W., Beauchet, O., & European GAITRite Network Group. (2006). Guidelines for clinical applications of spatio-temporal gait analysis in older adults. *Aging Clinical and Experimental Research*, 18, 174–176.
- Leitner, Y., Barak, R., Giladi, N., Peretz, C., Eshel, R., Gruendlinger, L., & Hausdorff, J. M. (2007). Gait in attention deficit hyperactivity disorder: Effects of methylphenidate and dual tasking. *Journal of Neurology*, 254, 1330–1338.
- Lemola, S. (2015). Long-term outcomes of very preterm birth. *European Psychologist*, 20, 128–137.
- Lim, B. O., O'Sullivan, D., Choi, B. G., & Kim, M. Y. (2016). Comparative gait analysis between children with autism and age-matched controls: Analysis with temporal-spatial and foot pressure variables. *Journal of Physical Therapy Science*, 28, 286–292.
- Liu, T., & Breslin, C. M. (2013). Fine and gross motor performance of the MABC-2 by children with autism spectrum disorder and typically developing children. *Research in Autism Spectrum Disorders*, 7, 1244–1249.
- Lord, S., Galna, B., & Rochester, L. (2013). Moving forward on gait measurement: Toward a more refined approach. *Movement Disorders*, 28, 1534–1543.
- Lord, S., Howe, T., Greenland, J., Simpson, L., & Rochester, L. (2011). Gait variability in older adults: A structured review of testing protocol and clinimetric properties. *Gait and Posture*, 34, 443–450.

- Lythgo, N., Wilson, C., & Galea, M. (2009). Basic gait and symmetry measures for primary school-aged children and young adults whilst walking barefoot and with shoes. *Gait and Posture*, 30, 502–506.
- Lythgo, N., Wilson, C., & Galea, M. (2011). Basic gait and symmetry measures for primary school-aged children and young adults II. Walking at slow, free and fast speed. *Gait and Posture*, 33, 29–35.
- Marcus, A., Sinnott, B., Bradley S., & Grey, I. (2010). Treatment of idiopathic toe-walking in children with autism using GaitSpot Auditory Speakers and simplified habit reversal. *Research in Autism Spectrum Disorders*, 4, 260–267.
- Marlow, N., Hennessy, E. M., Bracewell, M. A., & Wolke, D. (2007). Motor and executive function at 6 years of age after extremely preterm birth. *Pediatrics*, 120, 793–804.
- Martin, N. C., Piek, J., Baynam, G., Levy, F., & Hay, D. (2010). An examination of the relationship between movement problems and four common developmental disorders. *Human Movement Science*, 29, 799–808.
- McDonough, A. L., Batavia, M., Chen, F. C., Kwon, S., & Ziai, J. (2001). The validity and reliability of the GAITRite system's measurements: A preliminary evaluation. *Archives of Physical Medicine and Rehabilitation*, 82, 419–425.
- Minshew, N. J., Sung, K., Jones, B. L., & Furman, J. M. (2004). Underdevelopment of the postural control system in autism. *Neurology*, 63, 2056–2061.
- Mulder, H., Pitchford, N. J., Hagger, M. S., & Marlow, N. (2009). Development of executive function and attention in preterm children: A systematic review. *Developmental Neuropsychology*, 34, 393–421.
- Nayate, A., Tongue, B. J., Bradshaw, J. L., McGinley, J. L., Iansek, R., & Rinehart, N. J. (2012). Differentiation of high-functioning autism and Asperger's disorder based on neuromotor behaviour. *Journal of Autism and Developmental Disorders*, 42, 707–717.

- Nobile, M., Perego, P., Piccinini, L., Mani, E., Rossi, A., Bellina, M., & Molteni, M. (2010). Further evidence of complex motor dysfunction in drug naive children with autism using automatic motion analysis of gait. *Autism, 15*, 263–283.
- Nordin, V., & Gillberg, C. (1998). The long-term course of autistic disorders: Update on follow-up studies. *Acta Psychiatrica Scandinavica, 97*, 99–108.
- Nuysink, J., van Haastert, I. C., Eijssermans, M. J., Koopman-Esseboom, C., Helders, P. J., de Vries, L. S., & van der Net, J. (2013). Prediction of gross motor development and independent walking in infants born very preterm using the Test of Infant Motor Performance and the Alberta Infant Motor Scale. *Early Human Development, 89*, 693–697.
- Ozonoff, S., Young, G. S., Goldring, S., Greiss-Hess, L., Herrera, A. M., Steele, J., ... Rogers, S. J. (2008). Gross motor development, movement abnormalities, and early identification of autism. *Journal of Autism and Developmental Disorders, 38*, 644–656.
- Papadopoulos, N., McGinley, J. L., Bradshaw, J. L., & Rinehart, N. J. (2014). An investigation of gait in children with attention deficit hyperactivity disorder: A case controlled study. *Psychiatry Research, 218*, 319–323.
- Papadopoulos, N., McGinley, J., Tonge, B., Bradshaw, J., Saunders, K., Murphy, A., & Rinehart, N. (2012). Motor proficiency and emotional/behavioural disturbance in autism and Asperger's disorder: Another piece of the neurological puzzle? *Autism, 16*, 627–640.
- Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*, 220–244.
- Paquet, A., Olliac, B., Golse, B., & Vaivre-Douret, L. (2015). Current knowledge on motor disorders in children with autism spectrum disorder (ASD). *Child Neuropsychology*, 1–32. Advance online publication.

- Pasini, A., D'Agati, E., Pitzianti, M., Casarelli, L., & Curatolo, P. (2012). Motor examination in children with attention deficit/hyperactivity disorder and Asperger syndrome. *Acta Paediatrica*, 101, e15–e18.
- Petermann, F. (2008). *Movement Assessment Battery for Children* (2nd ed.). Frankfurt, Germany: Pearson Assessment.
- Petermann, F., & Petermann, U. (2011). *Wechsler Intelligence Scale for Children (WISC-IV)*. Frankfurt, Germany: Pearson Assessment.
- Piper, M. C. (1994). *Motor assessment of the developing infant*. Philadelphia, PA: Saunders.
- Provost, B., Lopez, B., & Heimerl, S. (2007). A comparison of motor delays in young children: Autism spectrum disorder, developmental delay, and developmental concerns. *Journal of Autism and Developmental Disorders*, 37, 321–328.
- Ravens-Sieberer, U., Gosch, A., Rajmil, L., Erhart, M., Bruil, J., Power, M., ... Mazur, J. (2008). The KIDSCREEN-52 Quality of Life Measure for Children and Adolescents: Psychometric Results from a Cross-Cultural Survey in 13 European Countries. *Value in Health*, 11, 645–658.
- Remscheid, H., & Kamp-Becker, I. (2007). Das Asperger Syndrom, eine Autismus-Spektrum-Störung. *Deutsches Ärzteblatt*, 104, 873–882.
- Rinehart, N. J., Tonge, B. J., Bradshaw, J. L., Iansek, R., Enticott, P. G., & McGinley, J. (2006). Gait function in high-functioning autism and Asperger's disorder. *European Child & Adolescent Psychiatry*, 15, 256–264.
- Rinehart, N. J., Tonge, B. J., Iansek, R., McGinley, J., Brereton, A. V., Enticott, P. G., & Bradshaw, J. L. (2006). Gait function in newly diagnosed children with autism: Cerebellar and basal ganglia related motor disorder. *Developmental Medicine & Child Neurology*, 48, 819–824.
- Saigal, S., & Doyle, L. W. (2008). An overview of mortality and sequelae of preterm birth from infancy to adulthood. *The Lancet*, 371, 261–269.

- Scafetta, N., Marchi, D., & West, B. J. (2009). Understanding the complexity of human gait dynamics. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 19, 026108.
- Schaefer, S., Lövdén, M., Wieckhorst, B., & Lindenberger, U. (2010). Cognitive performance is improved while walking: Differences in cognitive-sensorimotor couplings between children and young adults. *European Journal of Developmental Psychology*, 7, 371–389.
- Segawa, M., & Nomura, Y. (1991). Pathophysiology of human locomotion: Studies on clinical cases. In M. Shimamura, S. Grillner, & V. R. Edgerton (Eds.), *Neurobiological basis of human locomotion* (pp. 317–328). Tokyo, Japan: Japan Scientific Societies.
- Shaw, P., Eckstrand, K., Sharp, W., Blumenthal, J., Lerch, J. P., Greenstein, D. E. E. A., ... Rapoport, J. L. (2007). Attention-deficit/hyperactivity disorder is characterized by a delay in cortical maturation. *Proceedings of the National Academy of Sciences of the United States of America*, 104, 19649–19654.
- Shaw, P., Malek, M., Watson, B., Sharp, W., Evans, A., & Greenstein, D. (2012). Development of cortical surface area and gyrification in attention-deficit/hyperactivity disorder. *Biological Psychiatry*, 72, 191–197.
- Sheridan, P. L., Solomont, J., Kowall, N., & Hausdorff, J. M. (2003). Influence of executive function on locomotor function: Divided attention increases gait variability in Alzheimer's disease. *Journal of the American Geriatrics Society*, 51, 1633–1637.
- Shetreat-Klein, M., Shinnar, S., & Rapin, I. (2014). Abnormalities of joint mobility and gait in children with autism spectrum disorders. *Brain and Development*, 36, 91–96.
- Silk, T., Vance, A., Rinehart, N., Egan, G., O'Boyle, M., Bradshaw, J. L., & Cunnington, R. (2005). Fronto-parietal activation in attention-deficit hyperactivity disorder, combined type: Functional magnetic resonance imaging study. *The British Journal of Psychiatry*, 187, 282–283.

- Sparrow, W. A. (2000). *Energetics of human activities*. Champaign, IL: Human Kinetics.
- Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E. S., & Hausdorff, J. M. (2006). Dual-tasking effects on gait variability: The role of aging, falls, and executive function. *Movement Disorders, 21*, 950–957.
- Stansfield, B. W., Hillman, S. J., Hazlewood, M. E., Lawson, A. M., Mann, A. M., Loudon, I. R., & Robb, J. E. (2003). Normalisation of gait data in children. *Gait and Posture, 17*, 81–87.
- Steger, J., Imhof, K., Coutts, E., Gundelfinger, R., Steinhausen, H. C., & Brandeis, D. (2001). Attentional and neuromotor deficits in ADHD. *Developmental Medicine & Child Neurology, 43*, 172–179.
- Storvold, G. V., Aarethun, K., & Bratberg, G. H. (2013). Age for onset of walking and prewalking strategies. *Early Human Development, 89*, 655–659.
- Sutherland, D. H., Olshen, R., Biden, E. N., & Wyatt, M. P. (1988). *The development of mature walking*. Oxford, England: MacKeith.
- Teitelbaum, P., Teitelbaum, O., Nye, J., Fryman, J., & Maurer, R. (1998). Movement analysis in infancy may be useful for early diagnosis of autism. *Proceedings of the National Academy of Sciences of the United States of America, 95*, 13982–13987.
- Tervo, R. C., Azuma, S., Fogas, B., & Fiechtner, H. (2002). Children with ADHD and motor dysfunction compared with children with ADHD only. *Developmental Medicine & Child Neurology, 44*, 383–390.
- Thompson, K. (2007). *Medicines for mental health: The ultimate guide to psychiatric medication*. North Charleston, SC: Book Surge.
- Thorpe, D. E., Dusing, S. C., & Moore, C. G. (2005). Repeatability of temporospatial gait measures in children using the GAITRite electronic walkway. *Archives of Physical Medicine and Rehabilitation, 86*, 2342–2346.

- Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, 29, 3–18.
- Vaal, J., Van Soest, A. J., Hopkins, B., Sie, L. T. L., & Van der Knaap, M. S. (2000). Development of spontaneous leg movements in infants with and without periventricular leukomalacia. *Experimental Brain Research*, 135, 94–105.
- Van Damme, T., Simons, J., Sabbe, B., & van West, D. (2015). Motor abilities of children and adolescents with a psychiatric condition: A systematic literature review. *World Journal of Psychiatry*, 5, 315–329.
- Van Uden, C. J., & Besser, M. P. (2004). Test-retest reliability of temporal and spatial gait characteristics measured with an instrumented walkway system (GAITRite). *BMC Musculoskeletal Disorders*, 5, 13.
- Vernazza-Martin, S., Martin, N., Vernazza, A., Lepellec-Muller, A., Rufo, M., Massion, J., & Assaiante, C. (2005). Goal directed locomotion and balance control in autistic children. *Journal of Autism and Developmental Disorders*, 35, 91–102.
- Weiss, M. J., Moran, M. F., Parker, M. E., & Foley, J. T. (2013). Gait analysis of teenagers and young adults diagnosed with autism and severe verbal communication disorders. *Frontiers in Integrative Neuroscience*, 7.
- Wickens, C. D. (1991). Processing resources in attention. In D. L. Damos (Ed.), *Multiple-task performance* (pp. 3–34). Washington, DC: Taylor & Francis.
- Wilding, J. (2005). Is attention impaired in ADHD? *British Journal of Developmental Psychology*, 23, 487–505.
- Willcutt, E. G., Doyle, A. E., Nigg, J. T., Faraone, S. V., & Pennington, B. F. (2005). Validity of the executive function theory of attention-deficit/hyperactivity disorder: A meta-analytic review. *Biological Psychiatry*, 57, 1336–1346.

- Williams, J., Lee, K. J., & Anderson, P. J. (2010). Prevalence of motor-skill impairment in preterm children who do not develop cerebral palsy: A systematic review. *Developmental Medicine & Child Neurology*, 52, 232–237.
- Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. *Gait and Posture*, 16, 1–14.
- World Health Organization. (1992). The ICD-10 classification of mental and behavioural disorders: Clinical and diagnostic guidelines. Geneva, Switzerland: World Health Organization.
- Yogev, G., Giladi, N., Peretz, C., Springer, S., Simon, E. S., & Hausdorff, J. M. (2005). Dual tasking, gait rhythmicity, and Parkinson's disease: Which aspects of gait are attention demanding? *European Journal of Neuroscience*, 22, 1248–1256.
- Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders*, 23, 329–342.
- Zilbovicius, M., Garreau, B., Samson, Y., Remy, P., Barthelemy, C., Syrota, A., & Lelord, G. (1995). Delayed maturation of the frontal cortex in childhood autism. *American Journal of Psychiatry*, 152, 248–252.

APPENDIX A: Article 1

Hagmann-von Arx, P.⁺, Manicolo, O.⁺, Lemola, S., & Grob, A. (2016). Walking in school-aged children in a dual-task paradigm is related to age but not to cognition, motor behavior, injuries, or psychosocial functioning. *Frontiers in Psychology*, 7, 352.

(⁺shared first authorship)



Walking in School-Aged Children in a Dual-Task Paradigm Is Related to Age But Not to Cognition, Motor Behavior, Injuries, or Psychosocial Functioning

Priska Hagmann-von Arx^{1*}, Olivia Manicolo^{1†}, Sakari Lemola² and Alexander Grob¹

¹ Department of Psychology, University of Basel, Basel, Switzerland, ² Department of Psychology, University of Warwick, Coventry, UK

OPEN ACCESS

Edited by:

Petra Hauf,
St. Francis Xavier University, Canada

Reviewed by:

Ruth Ford,
Anglia Ruskin University, UK
Simone V. Gill,
Boston University, USA

*Correspondence:

Priska Hagmann-von Arx
priska.hagmann@unibas.ch

[†] Shared first authorship.

Specialty section:

This article was submitted to
Developmental Psychology,
a section of the journal
Frontiers in Psychology

Received: 14 December 2015

Accepted: 25 February 2016

Published: 10 March 2016

Citation:

Hagmann-von Arx P, Manicolo O,
Lemola S and Grob A (2016) Walking
in School-Aged Children in a
Dual-Task Paradigm Is Related to Age
But Not to Cognition, Motor Behavior,
Injuries, or Psychosocial Functioning.
Front. Psychol. 7:352.
doi: 10.3389/fpsyg.2016.00352

Age-dependent gait characteristics and associations with cognition, motor behavior, injuries, and psychosocial functioning were investigated in 138 typically developing children aged 6.7–13.2 years ($M = 10.0$ years). Gait velocity, normalized velocity, and variability were measured using the walkway system GAITRite without an additional task (single task) and while performing a motor or cognitive task (dual task). Assessment of children's cognition included tests for intelligence and executive functions; parents reported on their child's motor behavior, injuries, and psychosocial functioning. Gait variability (an index of gait regularity) decreased with increasing age in both single- and dual-task walking. Dual-task gait decrements were stronger when children walked in the motor compared to the cognitive dual-task condition and decreased with increasing age in both dual-task conditions. Gait alterations from single- to dual-task conditions were not related to children's cognition, motor behavior, injuries, or psychosocial functioning.

Keywords: gait, dual-task walking, intelligence, executive functions, psychosocial functioning, school-aged children

INTRODUCTION

Walking is the most important mode of human locomotion (Adolph et al., 2003) and is a remarkably complex motor skill involving neural control systems that produce coordinated limb movements (Hausdorff, 2007). There is evidence that among typically developing children a mature gait pattern is established at about 7 years (Adolph et al., 2003). However, some studies investigating older children have shown that gait variability – subtle stride-to-stride fluctuations reflecting the regularity of a gait pattern – continues to develop across childhood into adolescence (e.g., Hausdorff et al., 1999).

Performing concurrent tasks, like listening to a conversation while walking, is an everyday behavior. Such dual-task situations adversely affect children's walking, indicating that the regulation of gait requires cognitive processes such as executive and attentional functions (e.g., Cherng et al., 2007). Studies investigating children with developmental impairments have shown that children with motor and cognitive deficits are more vulnerable to dual-task gait decrements than typically developing children (e.g., Cherng et al., 2009; Katz-Leurer et al., 2011). Such decrements, in turn, may affect children's motor behavior and psychosocial functioning, as it is

known that children with poor motor skills participate in physical activity less frequently than controls (Cairney et al., 2005) and are at higher risk for peer rejection (Bejerot et al., 2013) as well as for social and emotional problems (Zwicker et al., 2012). However, these studies investigated children with developmental impairments, so it is still unclear if the maturity of walking patterns is related to cognition, motor behavior, and psychosocial functioning in typically developing children.

The aim of the present study was to shed light on age-dependent gait characteristics with a focus on gait variability in single- and dual-task walking and for the first time to examine the relation of dual-task effects on gait to cognition, motor behavior, and injuries, as well as psychosocial functioning in typically developing school-aged children.

After typically developing children master independent walking at approximately 12 to 14.5 months of age (Storvold et al., 2013), gait development is characterized by rapid improvements over the subsequent months (Bril and Ledebt, 1998; Adolph et al., 2003) until by the age of 3 years the visually apparent unsteadiness in walking has been replaced by a more stable gait pattern (Sutherland et al., 1988). With increasing age children show more subtle improvements in spatiotemporal gait parameters, including enhanced gait velocity and step length, and reach a mature gait pattern at about 7 years (e.g., Hillman et al., 2009; Holm et al., 2009). However, depending on the assessed gait parameters, there is evidence that gait continues to develop beyond this age (Hausdorff et al., 1999; Hillman et al., 2009; Lythgo et al., 2009, 2011; Froehle et al., 2013; Manicolo et al., 2016). For example, Hausdorff et al. (1999) investigated gait in typically developing children between 3 and 14 years of age. They measured gait velocity – considered a marker of general functional performance (cf. Al-Yahya et al., 2011) – as well as stride-to-stride fluctuations in spatiotemporal parameters (i.e., gait variability), which are sensitive to subtle physiological changes such as neural maturation and are believed to reflect the automaticity and regularity of gait (cf. Hausdorff, 2005). Results revealed that gait velocity was lowest in the youngest age group (aged 3 and 4 years) but did not significantly differ in the middle (aged 6 and 7 years) compared to the oldest (aged 11–14 years) age group, indicating a maturation of gait velocity at approximately 7 years of age. Results regarding gait variability showed a different picture. Gait variability continuously decreased from the youngest to the middle to the oldest age group. Thus, gait further developed after age 7 by becoming more automated and regular during middle and late childhood. In line with Hausdorff et al.'s (1999) findings, results of a recent study conducted by Abbruzzese et al. (2014) showed that when comparing gait variability of typically developing children aged 7–10 years to that of adults, children walked with significantly higher gait variability.

These findings indicate that among typically developing children gait variability decreases with age and that a mature gait pattern involving a high level of automaticity and regularity indicated by low gait variability may not be completely developed in school-aged children. Furthermore, these results highlight the sensitivity of gait variability measures and indicate their relevance

when investigating children's development of gait (Hausdorff, 2007).

In everyday life children usually do things concomitantly while walking, for example, listening to someone talk or fastening their jacket buttons. Such concurrent tasks may interfere with walking as less attention can be directed to the regulation of gait. Walking was for many years considered an automatic activity with only little involvement of cognitive processing. However, studies using a dual-task paradigm showed that gait is adversely affected when individuals are asked to walk and perform a concurrent task, indicating that walking requires cognitive resources (Huang and Mercer, 2001; Woollacott and Shumway-Cook, 2002; Huang et al., 2003; Cherg et al., 2007; Gill, 2015). Two theories have been used to explain dual-task effects on gait. The capacity-sharing theory proposes that attentional resources are limited in capacity and have to be shared between two tasks (Kahneman, 1973; Tombu and Jolicoeur, 2003). Researchers have suggested that gait decrements occur when the attentional demands of the concurrent task exceed the attentional resource capacity available (Huang and Mercer, 2001; Woollacott and Shumway-Cook, 2002). In contrast, the bottleneck theory (Pashler, 1994) proposes that two tasks that are performed simultaneously can only be carried out sequentially. This poses high demands on the capacity to switch between tasks, which in turn may lead to diminished performance in one or both of the tasks. However, there is currently no agreement on which theory best explains cognitive processing and dual-task effects (Yogev-Seligmann et al., 2008).

Studies investigating dual-task gait in typically developing children showed that performing a concurrent task while walking caused gait decrements (Huang et al., 2003; Cherg et al., 2007; Boonyong et al., 2012; Hung et al., 2013), indicating that also in children cognitive processes are involved when walking. Most studies on dual-task gait in children investigated spatiotemporal gait parameters such as velocity or stride length (e.g., Cherg et al., 2007; Boonyong et al., 2012; Hung et al., 2013), whereas only a few studies investigated gait variability. These revealed inconsistent results, with some researchers reporting no effect of dual tasking on gait variability (Leitner et al., 2007; Katz-Leurer et al., 2013; Abbruzzese et al., 2014) and others showing an increase in gait variability (Schaefer et al., 2010). However, the sample sizes in these studies were small, limiting the statistical power of these analyses.

Regarding age-dependent differences in dual-task gait, the effects of concurrent tasks on walking are stronger for younger compared to older typically developing children or adults. For example, Boonyong et al. (2012) examined the effect of an auditory concurrent task on spatiotemporal gait parameters in children aged 5 and 6 years, children aged 7–16 years, and healthy adults. Gait decrements such as reduced gait velocity in dual-task conditions were more profound in the younger compared to the older children and were greater in the two groups of children compared to the adults. Further, the study by Abbruzzese et al. (2014) revealed greater dual-task effects on gait variability in typically developing children aged 7–10 years compared to adults when they had to

perform concurrent motor tasks such as carrying a tray with a pitcher, indicating that dual-task gait is still developing during childhood.

Furthermore, there is evidence that dual-task gait decrements are apparent for both motor and cognitive concurrent tasks. For instance, Chergo et al. (2007) investigated typically developing children aged 4–6 years while they walked and concurrently performed an easy or a difficult motor (carrying a tray with or without marbles on it) or cognitive (repeating a series of digits forward or backward) task. Results revealed that children showed poorer walking performance in the difficult motor task condition as well as in both cognitive task conditions compared to single-task walking. Comparing gait decrements caused by the different dual-task conditions revealed inconsistent results. The concurrent motor task led to greater decreases in stride length and greater increases in double limb support (i.e., the percentage of a gait cycle when both feet are on the ground) compared to the concurrent cognitive task. In contrast, the concurrent cognitive tasks led to greater increases in base of support (i.e., the area between the feet in contact with the ground), while effects on velocity and cadence (i.e., steps per minute) were not significantly different between task conditions. From a theoretical point of view the multiple-resource model of attention (Wickens, 1991) assumes that two tasks will interfere with each other if they share the same pool of resources. Therefore, one might expect that walking while performing a concurrent cognitive task might not cause the same level of gait decrements as a concurrent motor task that shares resources with walking (Yogev-Seligmann et al., 2008).

Studies investigating children with developmental impairments showed that dual-task effects on gait are stronger in children with poor motor skills (Chergo et al., 2009) and that also children with deficits in executive and attentional functions show more gait alterations while dual tasking than typically developing children. For example, children with severe post-traumatic brain injury showed reduced gait velocity as well as higher gait variability when they had to walk and concomitantly memorize and recall a series of numbers or listen to and identify commonly experienced sounds compared to typically developing children (Katz-Leurer et al., 2011). Further, children born very preterm walked with comparable gait velocity but higher stride velocity variability than their peers born at term when they had to listen to and memorize digits (Hagmann-von Arx et al., 2015). Similarly, studies investigating adults showed that dual-task effects on gait and particularly on gait variability are more profound in older individuals (Beurskens and Bock, 2012) and in patients with neurological impairments (Al-Yahya et al., 2011) who exhibit deficits in executive and attentional functions. Executive functions refer to higher cognitive processes that include the control and allocation of attentional resources necessary for adaptive planning of behaviors (Anderson, 2002). It is assumed that lower executive functions are associated with a reduced capacity to divide attention among multiple tasks and, therefore, go along with higher gait alterations in dual-task situations, as individuals are kept from devoting the appropriate attentional resources to their gait (Springer et al., 2006; Leitner et al., 2007).

To our knowledge, however, no study has examined the relation between gait and cognition in typically developing school-aged children.

Motor performance affects other important aspects of children's development (Piek et al., 2006b). Independent walking alters an infant's relation to objects and people and allows the independent approach to new interaction partners (Iverson, 2010). These interactions, in turn, provide context for acquiring psychosocial skills (e.g., Karasik et al., 2011). However, motor skills that are not age-appropriately developed may negatively influence children's behavior and psychosocial functioning. For instance, children with poor motor skills perform more poorly in individual as well as in team games and sports (Cantell et al., 1994; Skinner and Piek, 2001), which may lead them to voluntarily withdraw from situations in which they might demonstrate their motor abilities (Schoemaker and Kalverboer, 1994). In a similar vein, there is evidence that children with impaired motor coordination spend more time alone and participate less often in physical activity such as social play or organized sports than typically developing children (Cairney et al., 2005), which in turn places further motor development at risk (Bouffard et al., 1996). For example, there is evidence that children with low levels of physical activity have an increased risk of injury (Bloemers et al., 2012). Furthermore, children with motor deficits may be perceived by peers as being different or awkward, which may lead to peer rejection (Bejerot et al., 2013). For example, there is evidence that children with poor motor skills are at higher risk of being bullied at school than children with average motor skills (Piek et al., 2006a; Bejerot and Humble, 2013; Bejerot et al., 2013). Withdrawal from or exclusion by the peer group may lead to decreased self-esteem in children with poor motor skills, which in turn may increase emotional and behavioral problems such as symptoms of anxiety and depression (Zwicker et al., 2012).

Taken together, the evidence suggests that (a) in typically developing school-aged children gait is still developing in single and dual tasking, particularly regarding its regularity, (b) children with cognitive deficits show more gait decrements in dual-task conditions, and (c) poor motor skills are related to other aspects of children's development. However, there are important gaps in the research. First, studies investigating age-dependent gait characteristics that include gait variability in single- and dual-task conditions in typically developing school-aged children are rare. Second, studies examining associations between dual-task gait effects and cognition in typically developing children are missing. Finally, to date, no study has examined the relation between dual-task gait effects, motor behavior, injuries, and psychosocial functioning in typically developing children.

In our study, we hypothesized the following: First, for single-task walking, we expected no association between age and gait velocity but hypothesized that age would be negatively related to gait variability, as the latter is sensitive to more subtle changes in gait (Hausdorff, 2005). Second, for dual-task walking, we hypothesized that age would be positively related to gait velocity and negatively related to gait variability, as there is evidence that dual-task gait is still developing (Boonyong et al., 2012; Abbruzzese et al., 2014). Third, we hypothesized that dual-task walking would lead to greater gait decrements (i.e., lower gait

velocity and higher gait variability) compared to single-task walking, with greater gait decrements in a motor compared to a cognitive dual-task condition, drawing on the assumption that tasks sharing the same pool of processing resources interfere with each other more strongly (Yogev-Seligmann et al., 2008). Fourth, we hypothesized that cognitive and motor task performance would be decreased in dual- compared to single-task conditions, following the capacity-sharing theory (Kahneman, 1973; Tombu and Jolicoeur, 2003) as well as the bottleneck theory (Pashler, 1994) suggesting that dual-task walking may not only affect gait but also concurrent task performance. Finally, we hypothesized that less dual-task gait effects (i.e., lower change in gait velocity and gait variability from single- to dual-task walking) would be related to better cognitive performance, better motor behavior (i.e., higher sports participation) lower injury risk, and fewer injuries, as well as higher psychosocial functioning (i.e., higher physical and psychological well-being, better moods and emotions, higher self-perception and autonomy, better parent relation, more financial resources, better social support, better school environment, as well as higher social acceptance), as suggested by the notion that motor performance also affects other domains of children's development (Piek et al., 2006b).

MATERIALS AND METHODS

Participants

A total of 141 children (63 girls, 78 boys, $M_{\text{age}} = 10.0$ years, $SD = 1.5$, age range: 6.7–13.2 years) were recruited from birth announcements in newspapers as well as from local schools in the German-speaking part of Switzerland. All children were screened for developmental coordination disorder using the German version of the Movement Assessment Battery for Children (2nd ed.) with a cut-off below the 16th percentile (Petermann, 2008). Three children were excluded because of significant motor impairment. The final sample for this study consisted of 138 typically developing school-age children aged 6.7–13.2 years ($M = 10.0$ years, $SD = 1.5$; 62 girls, 76 boys) enrolled in public primary schools.

The local Ethics Committee approved the study. Parents gave written informed consent for the children to participate and assent was obtained from the children.

Procedure

All children came to the laboratory for a visit that lasted approximately 3 h. Data were collected by trained study personnel. A battery of procedures was given in counterbalanced order to assess single- and dual-task gait and cognitive performance (i.e., intelligence, executive functions). In addition, children's weight was measured with a digital scale, height was measured with a fixed stadiometer, and leg length was measured from greater trochanter to the floor, bisecting the lateral malleolus, with the children wearing their normal clothes and footwear. Parents completed questionnaires to provide information on demographic data, as well as children's participation in sports, injury risk, and psychosocial functioning. Children received a gift voucher of CHF 30 for participating (1

CHF = 1.029 USD; February 2016) and parents received CHF 30 for completing the parental questionnaire.

Measures

Gait Assessment

Gait parameters were measured using a portable GAITRite electronic walkway system (GAITRite Platinum; CIR Systems, USA). This walkway system consists of an electronic mat (length: 7.01 m, width: 0.9 m) with 23,040 integrated pressure sensors. To minimize the effects of acceleration and deceleration, two electronically inactive sections each with a length of 1.25 m were added on each end of the walkway system. Hence, each walk covered a distance of approximately 10 m with an average of eight steps. Children's gait assessment using GAITRite has been established as reliable and valid (Thorpe et al., 2005). Gait analysis was performed according to European guidelines (Kressig and Beauchet, 2006). For each walk, the GAITRite software generates step-to-step values for a range of spatiotemporal gait parameters. The following gait parameters were derived: gait velocity which was measured in centimeters per second. In order to account for differences in children's leg length we additionally normalized gait velocity to a dimensionless quantity using the formula suggested by Hof (1996, p. 223):

$$\text{normalized velocity} = \frac{\text{gait velocity}}{\sqrt{(g \times l)}}$$

where g is the gravitational constant (9.81 m/s^2) and l is leg length. Further, we assessed gait variability as stride-to-stride variability in stride velocity, stride time, and stride length all expressed as the percentage coefficient of variation (standard deviation/mean $\times 100$).

Prior to gait assessment, children completed just the two tasks that would be used as the concurrent task for 10 s while standing so that their performance in these tasks could be determined. The concurrent tasks were selected according to related dual-task research. First, the children were asked to listen to and recall digits (digits task; Lindenberger et al., 2000; Leitner et al., 2007). For this task, children heard a list of randomized digits presented from a computer over loudspeakers that were installed at the front left and front right corner of the laboratory. Afterward, the children were asked to recall the digits. Second, children were asked to unfasten and fasten a button (button task) at stomach height (Ebersbach et al., 1995; Yang et al., 2007). Performance on this task was measured as the number of times the button could be unfastened and fastened.

Before the gait recordings, children were given one demonstration and one practice trial to familiarize them with the walkway system. Then, children were instructed to walk at their preferred pace without any additional task (single-task condition) with a total of four walking trials. Afterward, the children were instructed to walk at their preferred pace and to simultaneously perform one of the concurrent tasks (dual-task conditions) with two trials each. In the dual-task conditions children were not instructed to prioritize either one of the tasks. After each walk, gait data were analyzed using GAITRite software. For each child, gait parameters were averaged across

the corresponding trials for further data analysis. All children successfully completed all walking trials in the first attempt. However, for two children (aged 7.6 and 8.1 years) dual-task gait parameters are not available because of technical error of GAITRite during the testing session.

Cognitive Functions

Intelligence was assessed using the German version of the Wechsler Intelligence Scale for Children (4th ed., WISC-IV; Petermann and Petermann, 2011). The WISC-IV is an individually administered instrument for assessing intellectual abilities in children and adolescents aged 6–16 years with established reliability and validity (e.g., Daseking et al., 2007; Hagmann-von Arx et al., 2012). The WISC-IV comprises 10 core subtests and five supplemental subtests, which were not administered in the current study. The subtests are assigned to four index scores (verbal comprehension, perceptual reasoning, working memory, processing speed) and are combined to form the full-scale IQ with a mean of 100 ($SD = 15$), representing a child's global intellectual functioning. Due to restrictions in testing time intelligence scores are missing for six children.

Executive functions were measured using tasks from the computer-based Cambridge Neuropsychological Test Automated Battery (CANTAB touchscreen tests). CANTAB is suited for children aged from 4 years and provides highly reliable and valid measures for executive functions (e.g., Luciana, 2003). After a motor screening task, which introduced the CANTAB touchscreen to the children, they completed four tasks: The intra-extra dimensional (IED) set shift is a test of rule acquisition. It measures shifting and cognitive flexibility and records the number of errors made during the test. The rapid visual processing (RVP) test is a measure of vigilance or the ability to maintain a certain level of attention while engaged in a repetitive task. The outcome provides a measure of sensitivity to the target regardless of the response tendency. The stockings of Cambridge (SOC) task assesses the planning element of executive functions and records the number of problems solved in the minimum number of moves. Finally, the spatial working memory (SWM) test requires the child to maintain spatial information and to subsequently manipulate the presented items in working memory. The SWM task records the number of search errors. Scores reported in this study are standard scores based on age-corrected norms with $M = 0$ and $SD = 1$. Due to restrictions in testing time measures of executive functions are missing for six children.

Participation in Sports, Injury Risk, and Injuries

Parents reported whether their child was participating in sports. If yes, parents were further asked in which sport their child participated, how many times per week, and for how long. Scores for participation in sports reported in this study are number of minutes per week.

Parents also completed the German adaptation of the Injury Behavior Checklist (IBC; Brandau and Daghofer, 2010). The German IBC consists of 13 items regarding children's risk-taking behaviors that can lead to injury. Parents are asked to rate the

statements on a scale of 0 (*never*) to 3 (*very often*). The IBC has high reliability and established validity (Speltz et al., 1990; Brandau and Daghofer, 2010). Reliability in the present study was $\alpha = 0.76$.

To assess injuries, we asked parents to report whether their child had been injured in the past 24 months. If yes, parents were further asked to list all injuries and provide information regarding the location of the accident, the activity being performed while injured, the type of injury, and whether the injury had to be treated. Scores for injuries reported in this study are number of injuries in the past 24 months. These parental reports are available for 129 children.

Psychosocial Functioning

Psychosocial functioning was assessed using the German version of the KIDSCREEN-52, a parental questionnaire with proven reliability and validity (Ravens-Sieberger et al., 2008). KIDSCREEN-52 consists of 52 items assessing the frequency of behavior and feelings or the intensity of an attitude using a 5-point Likert scale with the anchor points 1 (*never*) and 5 (*always*). The items are assigned to 10 dimensions: physical well-being, psychological well-being, moods and emotions, self-perception, autonomy, parent relation and home life, peers and social support, school environment, social acceptance/bullying, and financial resources. Reliability in the present study ranged from $\alpha = 0.67$ (physical well-being) to $\alpha = 0.91$ (psychological well-being). The KIDSCREEN-52 is available for 128 children.

Statistical Procedure

Pearson's correlations were computed to assess the relations between children's demographic variables and all gait parameters in single- and dual-task conditions. Effects of age and dual-task conditions on gait were examined using repeated-measures multivariate analysis of variance (MANOVA) with one within-subject factor (walking condition: single-task vs. dual-task digits vs. dual-task button) and age as a continuous predictor. Significant effects were followed up with Bonferroni corrected *post hoc* pairwise comparisons. To assess effects of age on concurrent task performance, repeated-measures ANOVAs were performed separately for each walking condition with one within-subject factor (task performance: single task vs. dual task) and age as a continuous predictor. Extreme values in gait parameters defined as scores exceeding 3 SD s from the mean were truncated to $\pm 3 SD$. The level of significance was set to 0.05. The F statistic, p -values (two-tailed), and effect sizes (η^2) as well as regression parameter estimates (standardized beta coefficients) for the relation of age to gait and concurrent task performance for each walking condition are reported.

To examine associations between gait and children's cognition, motor behavior, and injuries, as well as psychosocial functioning we first calculated mean change values which are the mean differences between single-task and dual-task values. Positive signs denote a decrease from single-task to dual-task walking in the respective gait parameter, whereas negative signs denote an increase from single-task to dual-task walking in the respective

gait parameter. Afterward, regression analyses with mean change values in gait parameters predicting children's cognition, motor behavior, injuries, and psychosocial functioning were calculated controlling for age. Because of the high number of regressions performed, the level of significance was set to $p < 0.01$ to reduce the probability of alpha error accumulation. To estimate the statistical power given the sample size of the study, *post hoc* power analyses were performed using G*Power (Faul et al., 2007). The chance of detecting medium-sized effects ($r = 0.30$) was 97% at a 0.01 alpha level. All analyses were performed using SPSS Statistics 22 for Apple Mac.

RESULTS

Means, standard deviations, and correlations among children's demographic characteristics and gait parameters in single- and dual-task conditions are provided in Table 1.

Age Effects on Gait in Single- and Dual-Task Conditions

Repeated-measures MANOVAs were used to analyze the effects of dual tasking and age on gait. Regarding gait velocity, results revealed a significant within-subject effect of walking condition (Wilks's multivariate test), $F(2,133) = 21.154$, $p < 0.001$, $\eta^2 = 0.241$. Pairwise comparisons revealed higher gait velocity in single-task walking compared to both dual-task conditions ($p < 0.001$) and higher gait velocity in the dual-task condition digits compared to button ($p < 0.001$). There was no significant between-subjects effect of age but a significant Walking Condition \times Age interaction (Wilks's multivariate test), $F(2,133) = 3.956$, $p = 0.021$, $\eta^2 = 0.056$: While the effect of age was not significant for single-task walking or the dual-task condition digits, it was significant for the dual-task condition button, such that older children walked with higher gait velocity than younger children when unfastening and fastening a button. The regression parameter estimates for the associations between age and gait velocity in each walking condition are depicted in Figure 1A.

Regarding normalized velocity, results revealed a significant within-subject effect of walking condition (Wilks's multivariate test), $F(2,130) = 28.720$, $p < 0.001$, $\eta^2 = 0.306$. Pairwise comparisons revealed higher normalized velocity in single-task walking compared to both dual-task conditions ($p < 0.001$) and higher normalized velocity in the dual-task condition digits compared to button ($p < 0.001$). The between-subjects effect of age was marginally significant, $F(1,131) = 3.141$, $p = 0.079$, $\eta^2 = 0.023$, such that older children walked with lower normalized velocity than younger children. Further, the Walking Condition \times Age interaction was significant (Wilks's multivariate test), $F(2,130) = 7.192$, $p < 0.001$, $\eta^2 = 0.100$, indicating that the effect of age on normalized velocity was stronger in the single-task condition compared to the dual-task conditions. The regression parameter estimates for the associations between age and normalized velocity in each walking condition are depicted in Figure 1B.

For stride velocity variability, repeated-measures MANOVAs revealed a significant within-subject effect of walking condition (Wilks's multivariate test), $F(2,133) = 8.229$, $p < 0.001$, $\eta^2 = 0.110$. Pairwise comparisons revealed lower variability in single-task walking compared to both dual-task walking conditions ($p < 0.001$) and lower variability in the dual-task condition digits compared to button ($p < 0.001$). Furthermore, there was a significant between-subjects effect of age, $F(1,134) = 22.990$, $p < 0.001$, $\eta^2 = 0.146$, such that older children walked with lower variability than younger children in all walking conditions. The Walking Condition \times Age interaction was marginally significant (Wilks's multivariate test), $F(2,133) = 2.800$, $p = 0.064$, $\eta^2 = 0.040$, indicating that the effect of age on gait variability tended to be stronger in the single-task condition and dual-task condition button compared to the dual-task condition digits. The regression parameter estimates for the associations between age and stride velocity variability in each walking condition are depicted in Figure 1C.

Regarding stride time variability, results revealed a significant within-subject effect of walking condition (Wilks's multivariate test), $F(2,133) = 4.546$, $p = 0.012$, $\eta^2 = 0.064$. Pairwise comparisons revealed lower variability in single-task walking compared to both dual-task conditions ($p < 0.001$) and lower variability in the dual-task condition digits compared to button ($p < 0.001$). Furthermore, there was a significant between-subjects effect of age, $F(1,134) = 13.328$, $p < 0.001$, $\eta^2 = 0.090$, such that older children walked with lower gait variability than younger children. There was no significant Walking Condition \times Age interaction. The regression parameter estimates for the associations between age and stride time variability in each walking condition are shown in Figure 1D.

Regarding stride length variability, results revealed a significant within-subject effect of walking condition (Wilks's multivariate test), $F(2,133) = 7.690$, $p = 0.001$, $\eta^2 = 0.104$. Pairwise comparisons revealed lower variability in single-task walking compared to both dual-task conditions ($p < 0.003$) and lower variability in the dual-task condition digits compared to button ($p < 0.001$). Furthermore, there was a significant between-subjects effect of age, $F(1,134) = 16.819$, $p < 0.001$, $\eta^2 = 0.112$, such that older children walked with lower gait variability than younger children. Finally, there was a significant Walking Condition \times Age interaction (Wilks's multivariate test), $F(2,133) = 3.114$, $p = 0.048$, $\eta^2 = 0.045$, such that the effect of age on gait variability was stronger in the dual-task condition button compared to single-task walking and the dual-task condition digits. The regression parameter estimates for the associations between age and stride length variability in each walking condition are shown in Figure 1E.

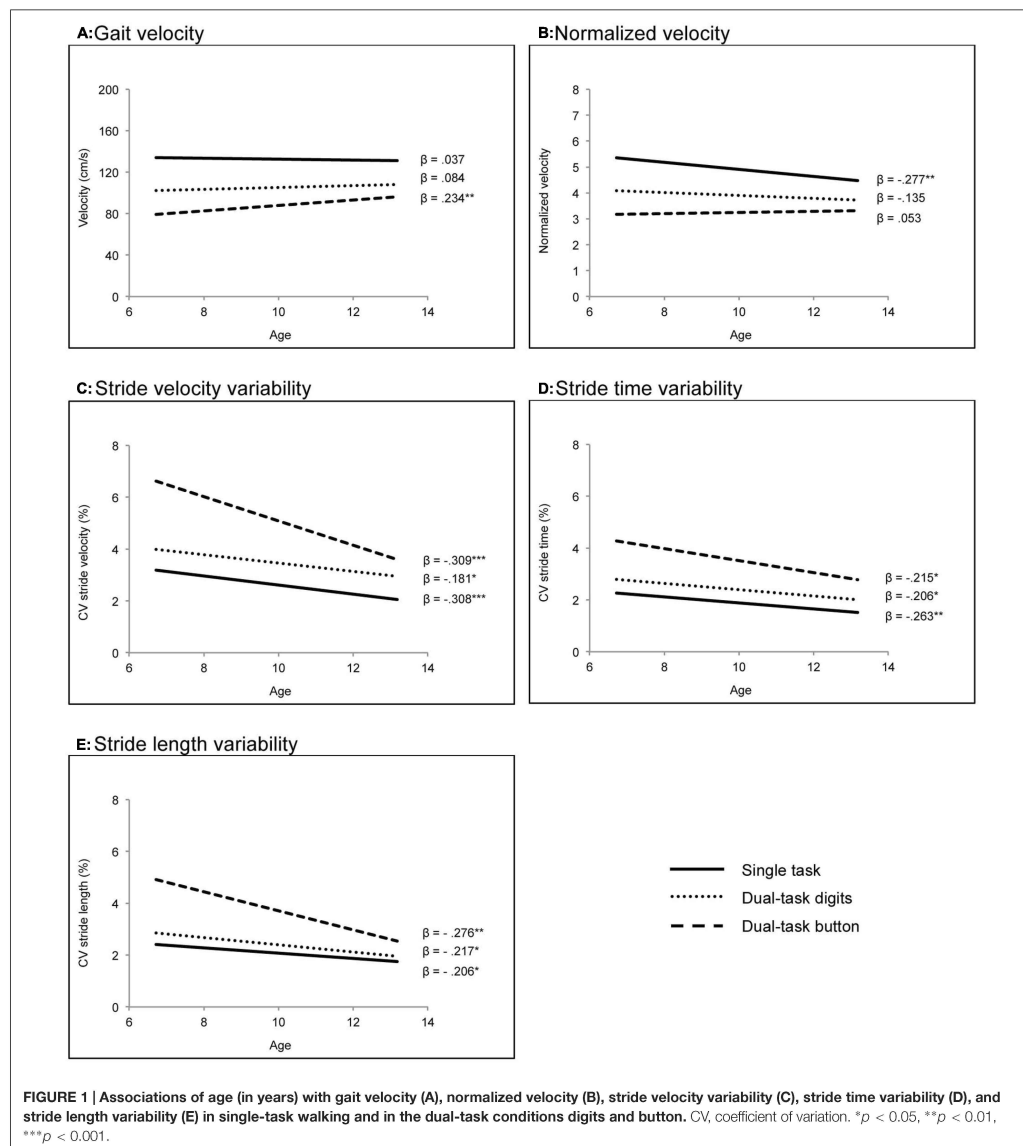
Age Effects on Concurrent Task Performance in Single- and Dual-Task Conditions

Children's performances of recalling digits in the single-task ($M = 3.94$, $SD = 0.89$) and dual-task ($M = 4.10$, $SD = 0.91$) conditions were comparable, $F(1,133) = 1.277$, $p = 0.260$, $\eta^2 = 0.010$. However, children's performance

TABLE 1 | Descriptive statistics and correlations for demographics and gait parameters.

Variable	M	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Demographics																					
1 Age	10.0	1.5	1																		
2 Sex (% male/female) ^a	–	–	–0.14	1																	
3 Height (cm)	141.7	10.6	0.79	–0.15	1																
4 Weight (kg)	35.0	8.6	0.68	–0.07	0.82	1															
5 Leg length (cm)	73.4	13.4	0.39	–0.09	0.55	0.47	1														
Single task																					
6 Velocity (cm/s)	132.6	19.0	–0.04	0.00	0.14	0.07	0.04	1													
7 Normalized velocity	4.9	0.7	–0.28	0.04	–0.20	–0.21	–0.27	0.94	1												
8 CV velocity (%)	2.6	0.9	–0.31	0.04	–0.28	–0.18	–0.20	–0.22	–0.12	1											
9 CV stride time (%)	1.9	0.6	–0.29	0.06	–0.30	–0.26	–0.18	–0.11	–0.01	0.57	1										
10 CV stride length (%)	2.1	0.7	–0.23	0.09	–0.28	–0.21	–0.24	–0.33	–0.23	0.71	0.40	1									
Dual task: digits																					
11 Velocity (cm/s)	105.3	16.0	0.08	0.04	0.10	–0.01	0.10	0.59	0.56	–0.23	–0.19	–0.31	1								
12 Normalized velocity	3.9	0.6	–0.14	0.08	–0.20	–0.25	–0.27	0.54	0.62	–0.14	–0.11	0.20	0.95	1							
13 CV velocity (%)	3.4	1.3	–0.18	–0.04	–0.15	–0.10	–0.01	–0.05	0.00	0.20	0.20	–0.29	–0.23	1							
14 CV stride time (%)	2.4	0.9	–0.21	–0.06	–0.20	–0.18	–0.08	–0.20	–0.13	0.33	0.32	0.25	–0.37	–0.29	0.64	1					
15 CV stride length (%)	2.4	1.0	–0.22	–0.12	–0.13	–0.07	–0.09	–0.08	–0.04	0.17	0.20	0.15	–0.36	–0.30	0.66	0.43	1				
Dual task: button																					
16 Velocity (cm/s)	88.1	16.9	0.23	–0.01	0.17	0.09	0.08	0.36	0.30	–0.19	–0.22	–0.31	0.66	0.59	–0.28	–0.35	–0.30	1			
17 Normalized velocity	3.2	0.6	0.05	0.01	–0.07	–0.09	–0.07	0.36	0.38	–0.12	–0.15	–0.24	0.68	0.68	–0.24	–0.31	–0.26	0.96	1		
18 CV velocity (%)	5.1	2.3	–0.31	0.02	–0.14	0.00	–0.04	0.11	0.14	0.16	0.12	0.13	–0.25	–0.20	0.20	0.22	0.25	–0.59	–0.56	1	
19 CV stride time (%)	3.5	1.6	–0.22	0.00	–0.08	0.02	–0.06	0.03	0.06	0.16	0.13	0.17	–0.31	–0.28	0.14	0.31	0.23	–0.60	–0.59	0.77	1
20 CV stride length (%)	3.7	2.0	–0.28	–0.05	–0.16	–0.07	–0.11	0.00	0.07	0.18	0.12	0.24	–0.29	–0.22	0.12	0.27	0.27	0.55	–0.52	0.78	0.71

CV, coefficient of variation. ^a0 = male, 1 = female; Significance: $p < 0.05$; $r > 0.17$; $p < 0.01$; $r > 0.22$; $p < 0.001$; $r > 0.27$.



increased with age, $F(1,133) = 12.674$, $p < 0.001$, $\eta^2 = 0.087$; Regression parameter estimates were $\beta = 0.295$, $p < 0.001$ for the single-task condition and $\beta = 0.220$, $p = 0.010$ for the dual-task condition. There was no significant Task Performance \times Age interaction, $F(1,133) = 0.702$, $p = 0.403$, $\eta^2 = 0.005$.

Children's performances of unfastening and fastening a button in the single-task ($M = 5.16$, $SD = 1.67$) and dual-task ($M = 6.31$, $SD = 1.90$) conditions were not significantly different, $F(1,132) = 2.509$, $p = 0.116$, $\eta^2 = 0.019$, and were comparable across age [age: $F(1,132) = 3.524$, $p = 0.063$, $\eta^2 = 0.026$; interaction: $F(1,132) = 0.159$, $p = 0.691$, $\eta^2 = 0.001$]; regression

parameter estimates were $\beta = 0.171$, $p = 0.050$ for the single-task condition and $\beta = 0.119$, $p = 0.172$ for the dual-task condition.

Gait and Associations with Cognition, Motor Behavior, and Injuries, as well as Psychosocial Functioning

Means and standard deviations of children's cognitive performance, motor behavior, and injuries, as well as psychosocial functioning are presented in **Table 2**.

Mean change values between single-task and dual-task gait parameters are presented in **Table 3**. The mean change values were positive for both velocity parameters, indicating a decrease in gait velocity and normalized velocity from single- to dual-task walking, whereas the mean change values were negative for all gait variability parameters, indicating an increase in gait variability from single- to dual-task walking. Regression analyses were calculated to examine the relation between mean change values in gait parameters and children's cognition, motor behavior, and injuries, as well as psychosocial functioning. Results are shown in **Table 3**. Controlling for age, there were no significant associations between mean change values in gait

parameters and other aspects of children's development (all $p \geq 0.01$).

DISCUSSION

The aim of the present study was to investigate age-dependent gait characteristics in single- and dual-task walking and to examine the relation of gait to cognition, motor behavior, and injuries, as well as psychosocial functioning for the first time in typically developing school-aged children. In single-task walking the present study revealed no association between age and gait velocity. This is in accordance with previous research, indicating a maturation of gait velocity at the age of 6–7 years (Hausdorff et al., 1999). However, a negative relation was found between age and normalized velocity. Thus, when accounting for differences in leg length of the children, which were correlated with age and therefore may have confounded our results, older children showed lower velocity than younger children. This finding contradicts previous results where normalized gait velocity was unaffected by age (Dusing and Thorpe, 2007). However, in our study velocity was normalized to leg length (Hof, 1996) whereas Dusing and Thorpe (2007) normalized data to height. Hence, due to the differing methods of normalization, it may not be possible to directly compare the results.

Further, a negative relation was found between age and gait variability what is in line with previous research showing higher gait variability in younger compared to older typically developing school-aged children (Hausdorff et al., 1999). These results provide evidence that gait variability, which is sensitive to more subtle physiological changes such as neural maturation than spatiotemporal gait parameters (Hausdorff, 2005), continues to develop across middle childhood into adolescence. Further, our results highlight the importance of not only assessing spatiotemporal gait parameters but also considering gait variability as an index of gait automaticity and regularity when investigating typically developing children's gait maturation, because these gait measures seem to undergo temporally distinct developmental trajectories.

In dual-task conditions, where children were asked to walk and simultaneously perform a concurrent cognitive task (i.e., listening to and memorizing digits) or motor task (i.e., unfastening and fastening a button), children walked with reduced gait velocity and normalized gait as well as increased gait variability compared to single-task walking. These results are in line with previous research showing that dual-task walking leads to gait decrements in spatiotemporal gait parameters (Cherng et al., 2007; Boonyong et al., 2012; Hung et al., 2013) as well as in gait variability measures (Schaefer et al., 2010), although other studies showed no effect of dual-task walking on gait variability in typically developing children (Leitner et al., 2007; Katz-Leurer et al., 2013; Abbruzzese et al., 2014). Our result that gait was adversely affected when children were asked to walk and perform a concurrent task supports the notion that gait requires cognitive resources (Huang and Mercer, 2001; Woollacott and Shumway-Cook, 2002; Huang et al., 2003; Cherng et al., 2007).

TABLE 2 | Means and standard deviations of children's cognition, motor behavior and injuries, as well as psychosocial functioning.

Variable	n	M	SD	Range
Cognition				
Intelligence (WISC-IV FSIQ)	132	105.94	10.48	84–136
Executive functions (CANTAB)				
IED	131	0.24	1.04	–6.64–1.89
RVP	127	–0.09	1.23	–4.96–1.25
SOC	132	0.01	0.83	–2.61–1.66
SWM	131	0.38	0.89	–2.22–2.75
Motor behavior and injuries				
Participation in sports (minutes/week)	129	214.98	153.51	0–870
Injury risk (IBC)	129	6.20	3.84	0–21
Injuries (number)	127	0.97	1.17	0–5
Psychosocial functioning (KIDSCREEN-52)				
Physical well-being	125	20.91	2.95	12.50–25
Psychological well-being	126	26.01	3.41	14–30
Moods and emotions	126	11.47	3.45	7–23
Self-perception	126	22.30	2.52	12–25
Autonomy	127	20.75	2.61	13–25
Parent relation and home life	127	25.28	3.06	17–30
Financial resources	125	13.30	2.28	3–15
Social support and peers	127	25.16	3.78	8–30
School environment	128	25.91	3.43	12–30
Social acceptance (bullying)	128	4.40	1.68	3–10

CANTAB, Cambridge Neuropsychological Test Automated Battery; IBC, injury behavior checklist; IED, intra-extra dimensional set shift; RVP, rapid visual processing; SOC, stockings of Cambridge; SWM, spatial working memory; WISC-IV FSIQ, Wechsler Intelligence Scales for Children 4th ed., full-scale IQ.

TABLE 3 | Regression analyses with mean changes in gait predicting children's cognition, motor behavior and injuries, as well as psychosocial functioning controlled for age.

Mean changes	Cognition					Motor behavior and injuries					Psychosocial functioning									
	M	SD	FSIQ	IED	RVP	SOC	SWM	Sports	IBC	Injuries	PHW	PSW	ME	SP	AUT	PRHL	FR	SSP	SE	SA
Dual task: Digits																				
Velocity	27.3	16.2	0.01	0.04	-0.15	-0.05	0.07	0.03	0.10	0.06	0.09	0.02	-0.01	0.10	-0.03	0.03	-0.06	0.02	0.02	-0.10
Normalized velocity	1.0	0.6	-0.01	0.06	-0.14	-0.06	0.10	0.02	0.11	0.04	0.08	0.01	0.00	0.08	-0.03	0.03	-0.09	0.00	0.00	-0.08
CV velocity	-0.8	1.4	0.03	0.04	-0.03	0.16	-0.10	0.00	-0.13	0.11	-0.03	0.06	-0.10	-0.01	0.14	0.03	0.09	-0.03	0.12	-0.04
CV stride time	-0.3	1.1	0.02	-0.02	0.05	0.08	-0.08	-0.17	-0.13	-0.05	-0.09	-0.20	0.05	-0.04	0.09	-0.04	-0.01	-0.11	0.13	-0.03
CV stride length	-0.5	0.9	0.05	0.07	-0.11	0.11	-0.04	-0.06	-0.06	0.03	0.13	0.23	-0.13	0.07	0.17	0.21	0.19	0.05	0.19	-0.07
Dual task: Button																				
Velocity	44.5	20.4	0.01	0.00	-0.06	-0.16	0.00	-0.03	-0.13	0.05	-0.01	-0.04	0.07	0.07	-0.05	0.05	-0.03	0.03	0.11	-0.05
Normalized velocity	1.7	0.8	0.01	0.01	-0.06	-0.18	-0.01	-0.05	-0.10	0.05	0.00	-0.11	0.12	-0.02	-0.04	0.02	-0.05	0.01	0.05	-0.03
CV velocity	-2.5	2.3	0.07	0.07	0.06	0.10	0.02	0.08	0.06	0.09	0.10	0.10	0.16	0.05	0.03	0.03	-0.08	-0.07	0.23	-0.09
CV stride time	-1.6	2.0	-0.03	0.00	0.08	0.15	0.05	-0.04	0.03	0.06	0.09	0.13	-0.11	0.03	-0.02	0.02	-0.09	-0.07	0.15	-0.19
CV stride length	-1.6	1.7	0.07	0.04	-0.04	0.14	0.11	-0.02	-0.06	0.11	0.16	0.12	-0.15	0.07	-0.02	0.10	0.00	-0.05	0.17	-0.19

Coefficients are standardized regression coefficients if not otherwise indicated. FSIQ, full-scale IQ; IED, intra-extra dimensional set shift; RVP, rapid visual processing; SOC, stockings of Cambridge; SWIM, spatial working memory; IBC, injury behavior checklist; PHW, physical well-being; PSW, psychological well-being; ME, moods and emotions; SP, self-perception; PRHL, parent relation and home life; FR, financial resources; SSP, social support and peers; SE, school environment; SA, social acceptance (bullying); CV, coefficient of variation. All $p \geq 0.01$.

However, the underlying mechanisms for the here reported dual-task interference are not clear (Yogev-Seligmann et al., 2008). In accordance with the capacity-sharing theory (Kahneman, 1973; Tombu and Jolicoeur, 2003), it is possible that having to share limited attentional resources between two attention-demanding tasks lead to decreased task performance in one or both of the tasks. On the other hand, following the bottleneck theory (Pashler, 1994), which claims that two simultaneously performed tasks are cognitively processed sequentially, it may be that switching from one task to the other leads to diminished performance in one or both of the tasks. Therefore, we not only investigated whether gait parameters changed from single- to dual-task walking but also whether the concurrent task performance differed between single- and dual-task conditions. Results showed that, while gait parameters significantly changed from single- to dual-task walking, concurrent task performance (i.e., number of recalled digits and number of times a button could be unfastened and fastened) did not differ between single- and dual-task conditions. Hence, although children were not instructed to prioritize one task over the other, they possibly followed a "posture second" strategy (Bloem et al., 2006) by prioritizing the concurrent task over their walking performance.

Regarding age-dependent dual-task effects on gait, the results revealed that in the motor dual-task condition, age was positively related to gait velocity. This result is in line with previous research on typically developing children showing that younger children walked with lower gait velocity than older children when concurrently performing a second task (Boonyong et al., 2012). However, in our study there were no age-dependent dual-task effects on gait velocity in the cognitive dual-task condition. Normalized velocity showed no age-dependent dual-task effects. Further, in both dual-task conditions, age was negatively related to gait variability such that younger children walked with higher gait variability than older children when concurrently listening to and memorizing digits or unfastening and fastening a button. These results are in line with the study conducted by Abbruzzese et al. (2014) and indicate that gait in dual-task conditions is still developing in middle childhood.

Our results further show that the dual-task effects on walking differed between the two types of concurrent tasks: When walking and concurrently unfastening and fastening a button, children showed greater decrease in gait velocity and normalized velocity, as well as a greater increase in gait variability compared to when walking and concurrently listening to and memorizing digits. This finding indicates that a concurrent motor task may lead to greater dual-task gait decrements than a concurrent cognitive task and can be interpreted from the perspective of the multiple-resource model of attention (Wickens, 1991; Cherng et al., 2007). This model assumes that attentional resources are not unitary but are divided into various pools, which, for example, depend on the modality of input and response. Walking requires visual input and further involves the response of moving and controlling body segments, which Cherng et al. (2007) subsumed under the term somatosensation. The motor concurrent task of unfastening and fastening a

button also requires visual input as well as somatosensory response. In contrast, the cognitive concurrent task of listening to and recalling digits requires auditory input and involves vocal response. According to these assumptions, the motor dual-task competes more strongly for processing resources with walking (i.e., visual input and somatosensory response) than the cognitive dual-task, which may have led to greater dual-task gait decrements in the motor compared to the cognitive dual-task condition.

Further, performance in the concurrent cognitive task of listening to and memorizing digits was associated with age such that older children recalled more digits than younger children. This is in accordance with previous research showing that younger children score lower than older children in working memory tests (Gathercole et al., 2004). Performance in the motor task of unfastening and fastening a button, however, was not related to age.

Finally, we investigated whether change in gait from single- to dual-task conditions (i.e., dual-task gait effects) is associated with cognition and other aspects of children's development. Our results revealed no significant relations. Thus, we conclude that contrary to our hypothesis, dual-task gait effects were not meaningfully related to children's cognition, motor behavior, and injuries, or psychosocial functioning. It has to be noted that our hypotheses were derived from studies comparing individuals with cognitive and motor impairments to typically developing controls. For example, regarding cognition, there is evidence that children and adults with deficits in executive and attentional functions show more gait alterations in single- and dual-task conditions compared to controls (e.g., Al-Yahya et al., 2011; Katz-Leurer et al., 2013). Regarding motor behavior and injuries, previous research investigating children with poor motor skills showed that these children participate less often in organized sports (Cairney et al., 2005) and have an increased risk of injury (Bloemers et al., 2012) compared to controls. Regarding psychosocial functioning, such as social acceptance or psychological well-being, previous findings investigating children with poor motor skills showed that these children are at higher risk for being bullied at school (Piek et al., 2006a; Bejerot and Humble, 2013; Bejerot et al., 2013) or for showing symptoms of anxiety and depression (Zwicker et al., 2012). However, we are not aware of studies investigating direct relations between gait and cognition, motor behavior and injuries, and psychosocial functioning in typically developing children. Therefore, our study is the first to provide preliminary evidence that dual-task effects in gait velocity, normalized velocity, and gait variability are not related to these aforementioned aspects of child development during middle childhood. However, the dual-task gait decrements apparent in our study support the notion that also among typically developing children, cognitive processes play an important role in gait. Hence, future studies might investigate whether other cognitive processes that were not investigated in this study, such as inhibition (i.e., inhibiting a prepotent reaction in favor of a less automated response) or cognitive flexibility (i.e., directing the attentional focus from one task to another; Miyake et al., 2000), also contribute to gait performance of typically developing children.

Our study has strengths and limitations. We consider it a strength that gait characteristics were assessed using the GAITRite system, which has proved to be a valid method of measuring gait parameters in children and offers the possibility of reliably identifying subtle changes in gait (Thorpe et al., 2005). During gait assessment children wore their normal clothes and shoes and it was therefore possible to assess gait performance as it is exhibited under everyday circumstances. However, although we investigated age-dependent gait characteristics in single- and dual-task walking of school-aged children, it was not possible to determine at what age gait characteristics, which are still developing during middle childhood, reach maturity, as we did not investigate a comparison sample of adult participants. Furthermore, the children in our study were first asked to perform single-tasks followed by dual-tasks. Therefore, we cannot rule out the possibility that a practice effect benefited the concurrent task performance while dual-tasking. In order to further investigate practice effects, future studies might apply task conditions in counter-balanced order or they might include a control group, which repeats the tasks only in single-task conditions. Additionally, our analyses were performed on cross-sectional data, whereas the testing of developmental trends in single- and dual-task walking should include longitudinal data in future investigations. Future research might also include different types of concurrent tasks when investigating children's gait in dual-task conditions because previous research also showed interference effects on gait for visual and auditory concurrent tasks among typically developing children (Huang et al., 2003). Finally, we investigated gait in straight walking. Future studies might examine age-dependent gait characteristics of walking along curved trajectories (Belmonti et al., 2013), as curvilinear walking may be more common in our everyday life.

CONCLUSION

This study provides important information on age-related changes in gait during middle childhood. Our findings indicate that gait in typically developing children becomes more regular with increasing age in single- and dual-task walking, thereby highlighting the importance of including measures of gait variability when investigating gait development. Since we found dual-task gait decrements to be larger when walking and concurrently performing a motor compared to a cognitive task, our results underscore the importance of taking the type of concurrent task into account when investigating children's gait in a dual-task paradigm. Finally, our study revealed no association of dual-task gait effects with children's cognition, motor behavior and injuries, or psychosocial functioning, indicating that subtle dual-task effects on gait do not go along with other aspects of development in typically developing children during middle childhood.

AUTHOR CONTRIBUTIONS

PH and OM contributed to the study design, acquisition, analysis and interpretation of data. Drafted and revised the manuscript,

gave final approval, and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Both authors contributed the same amount of work to this paper. SL contributed to the analysis and interpretation of data, revised the manuscript, gave final approval, and agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. AG contributed to the study design and interpretation of data, revised the manuscript,

gave final approval, and agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

ACKNOWLEDGMENT

The authors wish to thank Nadine Perkinson-Gloor for support in data collection.

REFERENCES

- Abbruzzese, L. D., Ashwini, R. K., Bellows, R., Figueroa, K., Levy, J., Lim, E., et al. (2014). Effects of manual task complexity on gait parameters in school-aged children and adults. *Gait Posture* 40, 658–663. doi: 10.1016/j.gaitpost.2014.07.017
- Adolph, K. E., Vereijken, B., and Shrout, P. E. (2003). What changes in infant walking and why. *Child Dev.* 74, 475–497. doi: 10.1111/1467-8624.7402011
- Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, D., and Cockburn, J. (2011). Cognitive motor interference while walking: a systematic review and meta-analysis. *Neurosci. Biobehav. Rev.* 35, 715–728. doi: 10.1016/j.gaitpost.2010.09.017
- Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychol.* 8, 71–82. doi: 10.1076/chin.8.2.71.8724
- Bejerot, S., and Humble, M. B. (2013). Childhood clumsiness and peer victimization: a case-control study of psychiatric patients. *BMC Psychiatry* 13:68. doi: 10.1186/1471-244X-13-68
- Bejerot, S., Plenty, S., Humble, A., and Humble, M. B. (2013). Poor motor skills: a risk marker for bully victimization. *Aggress. Behav.* 39, 453–461. doi: 10.1002/ab.21489
- Belmonti, V., Cioni, G., and Berthoz, A. (2013). Development of anticipatory orienting strategies and trajectory formation in goal-oriented locomotion. *Exp. Brain Res.* 227, 131–147. doi: 10.1007/s00221-013-3495-3
- Beurskens, R., and Bock, O. (2012). Age-related deficits of dual-task walking: a review. *Neural Plast.* 2012:131608. doi: 10.1155/2012/131608
- Bloem, B. R., Grimbergen, Y. A. M., van Dijk, G., and Munneke, M. (2006). The "posture second" strategy: a review of wrong priorities in Parkinson's disease. *J. Neurol. Sci.* 248, 196–204. doi: 10.1016/j.jns.2006.05.010
- Bloemers, F., Collard, D., Paw, M. C. A., Van Mechelen, W., Twisk, J., and Verhagen, E. (2012). Physical inactivity is a risk factor for physical activity-related injuries in children. *Br. J. Sport Med.* 46, 669–674. doi: 10.1136/bjsports-2011-090546
- Boonyong, S., Siu, K. C., van Donkelaar, P., Chou, L. S., and Woollacott, M. H. (2012). Development of postural control during gait in typically developing children: the effects of dual-task conditions. *Gait Posture* 35, 428–434. doi: 10.1016/j.gaitpost.2011.11.002
- Bouffard, M., Watkinson, E. J., Thompson, L. P., Causgrove Dunn, J., and Romanow, S. K. E. (1996). A test of the activity deficit hypothesis with children with movement difficulties. *Adapt. Phys. Act. Q.* 13, 61–73.
- Brandau, H., and Daghofer, F. (2010). Elternfragebogen zur erfassung des unfallrisikos von jungen [Parental questionnaire for injury risk assessment of young boys]. *Diagnostica* 56, 33–45. doi: 10.1026/0012-1924/a000007
- Bril, B., and Ledebt, A. (1998). Head coordination as a means to assist sensory integration in learning to walk. *Neurosci. Biobehav. Rev.* 22, 555–563. doi: 10.1016/S0149-7634(97)00044-4
- Cairney, J., Hay, J. A., Faught, B. E., Wade, T. J., Corna, L., and Flouris, S. (2005). Developmental coordination disorder, generalized self-efficacy toward physical activity, and participation in organized and free play activities. *J. Pediatr.* 147, 515–520. doi: 10.1016/j.jpeds.2005.05.013
- Cantell, M., Smyth, M., and Ahonen, T. (1994). Clumsiness in adolescence: educational, motor, and social outcomes of motor delay detected at 5 years. *Adapt. Phys. Act. Q.* 11, 115–129.
- Cherng, R. J., Liang, L. Y., Chen, Y. J., and Chen, J. Y. (2009). The effects of a motor and a cognitive concurrent task on walking in children with developmental coordination disorder. *Gait Posture* 29, 204–207. doi: 10.1016/j.gaitpost.2008.08.003
- Cherng, R. J., Liang, L. Y., Hwang, I. S., and Chen, J. Y. (2007). The effect of a concurrent task on the walking performance of preschool children. *Gait Posture* 26, 231–237. doi: 10.1016/j.gaitpost.2006.09.004
- Daseking, M., Petermann, U., and Petermann, F. (2007). Intelligenzdiagnostik mit dem HAWIK-IV [Assessment of intelligence with the HAWIK-IV]. *Kindh Entwickl.* 16, 250–259. doi: 10.1026/0942-5403.16.4.250
- Dusing, S. C., and Thorpe, D. E. (2007). A normative sample of temporal and spatial gait parameters in children using the GAITRite® electronic walkway. *Gait Posture* 25, 135–139. doi: 10.1016/j.gaitpost.2006.06.003
- Ebersbach, G., Dimitrijevic, M. R., and Poewe, W. (1995). Influence of concurrent tasks on gait: a dual-task approach. *Percept. Motor Skills* 81, 107–113. doi: 10.2466/pms.1995.81.1.107
- Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/BF03193146
- Froehle, A. W., Nahhas, R. W., Sherwood, R. J., and Duren, D. L. (2013). Age-related changes in spatiotemporal characteristics of gait accompany ongoing lower limb linear growth in late childhood and early adolescence. *Gait Posture* 38, 14–19. doi: 10.1016/j.gaitpost.2012.10.005
- Gathercole, S. E., Pickering, S. J., Ambridge, B., and Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Dev. Psychol.* 40, 177–190. doi: 10.1037/0012-1649.40.2.177
- Gill, S. V. (2015). Walking to the beat of their own drum: how children and adults meet timing constraints. *PLoS ONE* 10:e0127894. doi: 10.1371/journal.pone.0127894
- Hagmann-von Arx, P., Grob, A., Petermann, F., and Daseking, M. (2012). Konkurrente validität des HAWIK-IV und der intelligence und development scales (IDS) [Concurrent validity of the HAWIK-IV and the intelligence and development scales (IDS)]. *Z. Kinder Jug. Psych.* 40, 41–50. doi: 10.1024/1422-4917/a000148
- Hagmann-von Arx, P., Manicolo, O., Perkinson-Gloor, N., Weber, P., Grob, A., and Lemola, S. (2015). Gait in very preterm school-aged children in dual-task paradigms. *PLoS ONE* 10:e0144363. doi: 10.1371/journal.pone.0144363
- Hausdorff, J. M. (2005). Gait variability: methods, modeling and meaning. *J. Neuroeng. Rehabil.* 2:19. doi: 10.1186/1743-0003-2-19
- Hausdorff, J. M. (2007). Gait dynamics, fractals and falls: finding meaning in the stride-to-stride fluctuations of human walking. *Hum. Mov. Sci.* 26, 555–589. doi: 10.1016/j.humov.2007.05.003
- Hausdorff, J. M., Zeman, L., Peng, C. K., and Goldberger, A. L. (1999). Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children. *J. Appl. Physiol.* 86, 1040–1047.
- Hillman, S. J., Stansfield, B. W., Richardson, A. M., and Robb, J. E. (2009). Development of temporal and distance parameters of gait in normal children. *Gait Posture* 29, 81–85. doi: 10.1016/j.gaitpost.2008.06.012
- Hof, A. L. (1996). Scaling gait data to body size. *Gait Posture* 4, 222–223. doi: 10.1016/0966-6362(95)01057-2
- Holm, I., Tveter, A. T., Frederiksen, P. M., and Vollestad, N. (2009). A normative sample of gait and hopping on one leg parameters in children 7–12 years of age. *Gait Posture* 27, 91–96. doi: 10.1016/j.gaitpost.2008.09.016
- Huang, H. J., and Mercer, V. S. (2001). Dual-task methodology: applications in studies of cognitive and motor performance in adults and children. *Pediatr. Phys. Ther.* 13, 133–140. doi: 10.1097/00001577-200113030-00005

- Huang, H. J., Mercer, V. S., and Thorpe, D. E. (2003). Effects of different concurrent cognitive tasks on temporal-distance gait variables in children. *Pediatr. Phys. Ther.* 15, 105–113. doi: 10.1097/01.PEP.0000067886.96352.6B
- Hung, Y. C., Meredith, G. S., and Gill, S. V. (2013). Influence of dual task constraints during walking for children. *Gait Posture* 38, 450–454. doi: 10.1016/j.gaitpost.2013.01.009
- Iverson, J. M. (2010). Developing language in a developing body: the relationship between motor development and language development. *J. Child Lang.* 37, 229–261. doi: 10.1017/S0305000909990432
- Kahneman, D. (1973). *Attention and Effort*. Englewood Cliffs, NJ: Prentice Hall.
- Karasik, L. B., Tamis-LeMonda, C. S., and Adolph, K. E. (2011). Transition from crawling to walking and infants' actions with objects and people. *Child Dev.* 82, 1199–1209. doi: 10.1111/j.1467-8624.2011.01595.x
- Katz-Leurer, M., Rotem, H., Keren, O., and Meyer, S. (2011). Effect of concurrent cognitive tasks on gait features among children post-severe traumatic brain injury and typically-developed controls. *Brain Inj.* 25, 581–586. doi: 10.3109/02699052.2011.572943
- Katz-Leurer, M., Rotem, H., and Meyer, S. (2013). Effects of concurrent cognitive tasks on temporo-spatial parameters of gait among children with cerebral palsy and typically developed controls. *Dev. Neurorehabil.* 17, 363–367. doi: 10.3109/17518423.2013.810676
- Kressig, R. W., and Beauchet, O. (2006). European GAITRite network group, guidelines for clinical applications of spatio-temporal gait analysis in older adults. *Aging Clin. Exp. Res.* 18, 174–176. doi: 10.1007/BF03327437
- Leitner, Y., Barak, R., Giladi, N., Peretz, C., Eshel, R., Gruendlinger, L., et al. (2007). Gait in attention deficit hyperactivity disorder: effects of methylphenidate and dual tasking. *J. Neurol.* 254, 1330–1338. doi: 10.1007/s00415-006-0522-3
- Lindenberger, U., Marsiske, M., and Baltes, P. (2000). Memorizing while walking: increase in dual-task costs from young adulthood to old age. *Psychol. Aging* 15, 417–436. doi: 10.1037/0882-7974.15.3.417
- Luciana, M. (2003). Practitioner review: computerized assessment of neuropsychological function in children: clinical and research applications of the cambridge neuropsychological testing automated battery (CANTAB). *J. Child Psychol. Psychiatry* 44, 649–663. doi: 10.1111/1469-7610.00152
- Lythgo, N., Wilson, C., and Galea, M. (2009). Basic gait and symmetry measures for primary school-aged children and young adults whilst walking barefoot and with shoes. *Gait Posture* 30, 502–506. doi: 10.1016/j.gaitpost.2009.07.119
- Lythgo, N., Wilson, C., and Galea, M. (2011). Basic gait and symmetry measures for primary school-aged children and young adults II. Walking at slow, free and fast speed. *Gait Posture* 33, 29–35. doi: 10.1016/j.gaitpost.2010.09.017
- Manicolo, O., Grob, A., Lemola, S., and Hagmann-von Arx, P. (2016). Age-related decline of gait variability in children with attention-deficit/hyperactivity disorder: support for the maturational delay hypothesis. *Gait Posture* 44, 245–249. doi: 10.1016/j.gaitpost.2015.12.012
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100. doi: 10.1006/cogp.1999.0734
- Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244. doi: 10.1037/0033-2909.116.2.220
- Petermann, F. (2008). *Movement Assessment Battery for Children*, 2nd Edn. Frankfurt: Pearson Assessment.
- Petermann, F., and Petermann, U. (2011). *Wechsler Intelligence Scale for Children (WISC-IV)*. Frankfurt: Pearson Assessment.
- Piek, J. P., Barrett, N. C., Allen, L. S. R., Jones, A., and Louise, M. (2006a). The relationship between bullying and self-worth in children with movement coordination problems. *Br. J. Educ. Psychol.* 75, 453–463. doi: 10.1348/000709904X24573
- Piek, J. P., Baynam, G. B., and Barrett, N. C. (2006b). The relationship between fine and gross motor ability, self-perception and self-worth in children and adolescents. *Hum. Mov. Sci.* 25, 65–75. doi: 10.1016/j.humov.2005.10.011
- Ravens-Sieberer, U., Gosch, A., Rajmil, L., Erhart, M., Bruil, J., Power, M., et al. (2008). The KIDSCREEN-52 quality of life measure for children and adolescents: psychometric results from a cross-cultural survey in 13 European countries. *Value Health* 4, 645–658. doi: 10.1111/j.1524-4733.2007.00291.x
- Schaefer, S., Lövdén, M., Wieckhorst, B., and Lindenberger, U. (2010). Cognitive performance is improved while walking: differences in cognitive-sensorimotor couplings between children and young adults. *Eur. J. Dev. Psychol.* 7, 371–389. doi: 10.1080/17405620802535666
- Schoemaker, M. M., and Kalverboer, A. F. (1994). Social and affective problems of children who are clumsy: how early do they begin. *Adapt. Phys. Act. Q.* 11, 130–140.
- Skinner, R. A., and Piek, J. P. (2001). Psychosocial implications of poor motor coordination in children and adolescents. *Hum. Mov. Sci.* 20, 73–94. doi: 10.1016/S0167-9457(01)00029-X
- Speltz, M. L., Gonzales, N., Sulzbacher, S., and Quan, L. (1990). Assessment of injury risk in young children: a preliminary study of the injury behavior checklist. *J. Pediatr. Psychol.* 15, 373–383. doi: 10.1093/jpepsy/15.3.373
- Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E. S., and Hausdorff, J. M. (2006). Dual-tasking effects on gait variability: the role of aging, falls, and executive function. *Mov. Disord.* 21, 950–957. doi: 10.1002/mds.20848
- Storvold, G. V., Aarethun, K., and Bratberg, G. H. (2013). Age for onset of walking and prewalking strategies. *Early Hum. Dev.* 89, 655–659. doi: 10.1016/j.earlhumdev.2013.04.010
- Sutherland, D. H., Olshen, R., Biden, E. N., and Wyatt, M. P. (1988). *The Development of Mature Walking*. Oxford: MacKeith.
- Thorpe, D. E., Dusing, S. C., and Moore, C. G. (2005). Repeatability of temporospatial gait measures in children using the GAITRite electronic walkway. *Arch. Phys. Med. Rehabil.* 86, 2342–2346. doi: 10.1016/j.apmr.2005.07.301
- Tombu, M., and Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *J. Exp. Psychol. Hum.* 29, 3–18. doi: 10.1037/0096-1523.29.1.3
- Wickens, C. D. (1991). "Processing resources in attention," in *Multiple-Task Performance*, ed. D. L. Damos (Washington, DC: Taylor & Francis), 3–34.
- Woollacott, M., and Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture* 16, 1–14. doi: 10.1016/S0966-6362(01)00156-4
- Yang, Y. R., Chen, Y. C., Lee, C. S., Cheng, S. J., and Wang, R. Y. (2007). Dual-task-related gait changes in individuals with stroke. *Gait Posture* 25, 185–190. doi: 10.1016/j.gaitpost.2006.03.007
- Yogev-Seligmann, G., Hausdorff, J. M., and Giladi, N. (2008). The role of executive function and attention in gait. *Mov. Disord.* 23, 329–342. doi: 10.1002/mds.21720
- Zwicker, J. G., Missiuna, C., Harris, S. R., and Boyd, L. A. (2012). Developmental coordination disorder: a review and update. *Eur. J. Paediatr. Neurol.* 16, 573–581. doi: 10.1016/j.ejpn.2012.05.005

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2016 Hagmann-von Arx, Manicolo, Lemola and Grob. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

APPENDIX B: Article 2

Hagmann-von Arx, P., Manicolo, O., Perkinson-Gloor, N., Weber, P., Grob, A., & Lemola, S. (2015). Gait in very preterm school-aged children in dual-task paradigms. *PLoS ONE*, *10*, e0144363.

RESEARCH ARTICLE

Gait in Very Preterm School-Aged Children in Dual-Task Paradigms

Priska Hagmann-von Arx^{1*}, Olivia Manicolo¹, Nadine Perkinson-Gloor¹, Peter Weber², Alexander Grob¹, Sakari Lemola¹

1 Department of Psychology, University of Basel, Basel, Switzerland, **2** Division of Neuropediatrics and Developmental Medicine, University Children's Hospital Basel, Basel, Switzerland

* priska.hagmann@unibas.ch



OPEN ACCESS

Citation: Hagmann-von Arx P, Manicolo O, Perkinson-Gloor N, Weber P, Grob A, Lemola S (2015) Gait in Very Preterm School-Aged Children in Dual-Task Paradigms. PLoS ONE 10(12): e0144363. doi:10.1371/journal.pone.0144363

Editor: Yuri P. Ivanenko, Scientific Institute Foundation Santa Lucia, ITALY

Received: July 5, 2015

Accepted: November 17, 2015

Published: December 7, 2015

Copyright: © 2015 Hagmann-von Arx et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the paper and its Supporting Information file.

Funding: This research was financially supported by the Swiss National Science Foundation (Project: Sleep, cognitive, and socio-emotional development in preterm children during middle and late childhood Grant number: 143962), and the Research Fund of the University of Basel. SL, PH, PW, AG received the funding. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Abstract

Objective

The control of gait requires executive and attentional functions. As preterm children show executive and attentional deficits compared to full-term children, performing concurrent tasks that impose additional cognitive load may lead to poorer walking performance in preterm compared to full-term children. Knowledge regarding gait in preterm children after early childhood is scarce. We examined straight walking and if it is more affected in very preterm than in full-term children in dual-task paradigms.

Study design

Twenty preterm children with very low birth-weight (≤ 1500 g), 24 preterm children with birth-weight > 1500 g, and 44 full-term children, born between 2001 and 2006, were investigated. Gait was assessed using an electronic walkway system (GAITRite) while walking without a concurrent task (single-task) and while performing one concurrent (dual-task) or two concurrent (triple-task) tasks. Spatio-temporal gait parameters (gait velocity, cadence, stride length, single support time, double support time), normalized gait parameters (normalized velocity, normalized cadence, normalized stride length) and gait variability parameters (stride velocity variability, stride length variability) were analyzed.

Results

In dual- and triple-task conditions children showed decreased gait velocity, cadence, stride length, as well as increased single support time, double support time and gait variability compared to single-task walking. Further, results showed systematic decreases in stride velocity variability from preterm children with very low birth weight (≤ 1500 g) to preterm children with birth weight > 1500 g to full-term children. There were no significant interactions between walking conditions and prematurity status.

Conclusions

Dual and triple tasking affects gait of preterm and full-term children, confirming previous results that walking requires executive and attentional functions. Birth-weight dependent

Competing Interests: The authors have declared that no competing interests exist.

systematic changes in stride velocity variability indicate poorer walking performance in pre-term children who were less mature at birth.

Introduction

The incidence of very preterm birth (i.e., birth before the 32nd gestational week) has been rising and survival rates of the very preterm have increased due to improved neonatal care [1]. This development is leading to an increased number of very prematurely born children who are entering public school today. However, even generally well-developing very preterm children who are enrolled in elementary school are at increased risk for several long-term sequels [2], including impairments in cognitive processes such as executive and attentional functions [3–5], and motor development [6], [7].

Motor skills affect important aspects of children's development [8]. Children with poor motor skills may voluntarily withdraw from situations in which they might show their lower motor abilities [9–12] what may put further motor development at risk [13]. In addition, children with poor motor skills may be perceived by peers as being different or awkward, which may lead to peer rejection [14–16]. Withdrawal from or exclusion by the peer group may both lead to decreased self-esteem, which in turn may increase emotional and behavioral problems [17].

However, although motor impairments have been studied in very preterm children [6], [7], there is scarce of knowledge regarding their development of walking—the most important mode of human locomotion [18].

Gait is a remarkably complex task involving neural control systems to produce coordinated limb movements [19]. Learning to walk freely is a milestone in motor development and requires a learning period of approximately 12 to 14.5 months in full-term infants [20]. Thereafter, gait is continuously stabilized until a mature walking pattern is reached at about 7 years [21]. However, there is evidence that gait continues to develop across childhood and adolescence [22–24]. For example, Hausdorff, Zeman, Peng, and Goldberger [22] showed that gait variability, reflecting the automaticity, rhythmicity, and regularity of gait [25], decreased from childhood to adolescence. In a related vein, Belmonti, Cioni, and Berthoz [24] showed that curvilinear walking, i.e. walking along curved trajectories, is not fully developed before children reach 11 years of age.

Studies with preterm infants indicate that the onset of independent walking is delayed [26–28]. During childhood and adolescence, preterm children show an increased risk for gross motor deficits in dynamic and static balance skills, such as heel walking and one-leg standing [5], [29], and report lower physical activity [30–32] and participation in organized sports [30], [32] than full-term peers. These patterns persist into adulthood [33–35].

Generally, it is acknowledged that executive and attentional functions are involved in the control of gait [36]. Executive functions refer to higher cognitive processes that include the control and allocation of attentional resources necessary for adaptive planning of behaviors [37]. Studies using a dual-task paradigm showed that gait is affected when participants are asked to walk and perform a concurrent task [38]. Studies also revealed that dual-task effects on gait variability are particularly profound in elderly individuals [39] and neurological patients [40–42], who show reduced executive and attentional functions [25], [36], [41–43]. Dual tasking also resulted in gait alterations in children, indicating that gait requires executive and attentional functions also during childhood [44–46]. The effects of dual tasking on gait were more profound in children with deficits in executive and attentional functions, such as children with severe post-traumatic brain injury [47].

In sum, research on gait in generally well-developing very preterm children is scarce. Moreover, the role that limitations in executive and attentional functions play in gait in very preterm children is unknown.

The main goal of the present study was therefore to assess gait and concurrent task performance in very preterm and full-term children in single-, dual-, and triple-task conditions. To achieve ecological validity the dual and triple tasks included tasks that are often required in children's everyday lives while walking, such as listening to someone talking. First, we expected to find impaired gait performance in dual- and triple-task conditions compared to a single-task walking condition in preterm and full-term children. Second, we expected to find more strongly compromised gait performance in very preterm compared to full-term children in dual- and triple-task conditions due to their deficits in executive and attentional functions. Particularly, we hypothesized that very preterm children show higher gait variability than full-term children in dual- and triple-task conditions. Finally, we expected to find decreased performance on the concurrent tasks in preterm compared to full-term children, assuming that concurrent walking would distract their attentional resources more strongly [48].

Materials and Methods

Participants

Forty-nine very preterm children were recruited from an initial cohort of 260 very preterm children, born between 2001 and 2006 and postnatally treated at the University Children's Hospital Basel (Switzerland). One hundred and two preterm children were excluded from the initial cohort due to no or incomplete information on the neurobehavioral development before age 2 or severe developmental delay, insufficient German language skills of parents to give informed consent, or residence outside of Switzerland or more than 100 km away from the study center. Additionally, 7 children could not be traced. Of the 151 parents who were contacted by phone, 49 agreed to allow their children to participate. Compared to nonparticipants, participating preterm children had a higher birth weight (1422 g vs. 1251 g, $F(1,150) = 5.46$, $p = .02$), higher gestational age (30.2 weeks vs. 29.3 weeks, $F(1,150) = 6.67$, $p = .01$), and a shorter hospital stay (46.5 days vs. 56.3 days, $F(1,148) = 5.89$, $p = .02$). Age- and sex-matched full-term children were recruited from birth announcements in newspapers and local schools. As parents of some full-term children refused participation, we were unable to recruit controls for two of the 49 preterm children. Therefore, these two preterm children were excluded from the present study. All children were screened for intellectual disability ($IQ \leq 70$) using the German version of the Wechsler Intelligence Scale for Children, 4th edition [49] and for developmental coordination disorder using the German version of the Movement Assessment Battery for Children, 2nd edition with a cut-off below the 16th percentile [50]. None of the children were excluded because of their IQ, whereas 3 preterm children and 1 full-term child were excluded because of significant motor impairment.

The final sample for this study consisted of 44 very preterm children (mean age = 9.48 years, 25 boys, < 32 weeks of gestation, mean birth weight = 1423 g) and 44 full-term children (mean age = 9.47 years, 24 boys, > 37 weeks of gestation, mean birth weight = 3353 g). The sample of preterm children included 20 children with very low birth weight (≤ 1500 g; mean birth weight: 1026 g) and 24 children with birth weight > 1500 g (mean birth weight: 1754 g). None of the children suffered from periventricular leukomalacia, while one of the 44 preterm children was diagnosed with mild intraventricular hemorrhage (IVH) grade 1. All children attended primary school in Switzerland. Preterm and full-term children were comparable regarding age, sex, height, weight, and leg length (Table 1).

Table 1. Demographic characteristics of preterm and full-term children.

Characteristic	Preterm			Full Term (D) Control (N = 44)	A vs. D		B vs. C. vs. D	
	(A) Total (N = 44)	(B) ≤1500 g (n = 20)	(C) >1500 g (n = 24)		P Value	P Value	Group Differences	
Age (years)	9.5 (1.3)	9.7 (1.4)	9.3 (1.3)	9.5 (1.3)	.994	.710		
Male gender	25 (57)	9 (45)	16 (67)	24 (55)	.830	.346		
Gestational age (weeks)	30.1 (2.1)	28.7 (2.3)	31.3 (0.7)	39.6 (1.5)	< .001	< .001		D>B>A
Birth weight (g)	1423 (421)	1026 (250)	1754 (168)	3353 (429)	< .001	< .001		D>B>A
Weight (kg)	32.4 (7.8)	30.2 (7.6)	34.0 (7.6)	33.4 (8.7)	.573	.269		
Height (cm)	139.0 (10.1)	137.6 (11.2)	140.1 (9.3)	138.2 (9.9)	.716	.660		
Leg length (cm) ^a	73.9 (6.9)	73.5 (7.3)	74.2 (6.6)	72.6 (7.5)	.392	.655		
IDS selective attention ^b	120.3 (26.0)	120.6 (27.3)	120.1 (25.7)	131.1 (25.3)	.091	.241		
SDQ hyperactivity/ inattention ^c	3.5 (2.3)	3.0 (1.6)	3.8 (2.6)	2.5 (2.4)	.093	.160		

Data are mean (SD) or number (%). *P* values are given for analyses of variance or χ^2 test. IDS, Intelligence and Development Scales; SDQ, Strength and Difficulties Questionnaire.

^a Leg length was measured with footwear from greater trochanter to the floor, bisecting the lateral malleolus.

^b Scores range from 0 to 225. Higher scores indicate better performance.

^c Scores range from 0 to 10. Higher scores indicate more difficulties.

doi:10.1371/journal.pone.0144363.t001

To screen for executive and attentional functions, we measured selective attention using the selective attention subtest of the Intelligence and Development Scales (IDS) [51], [52]. Additionally, we measured hyperactivity-inattention with the German version of the Strengths and Difficulties Questionnaire (SDQ) [53]. Results revealed a tendency towards lower IDS ($p = .091$) and higher SDQ ($p = .093$) scores in preterm compared to full-term children, indicating that executive and attentional functions were marginally lower in the preterm children of our study compared to full-term children.

The Ethics Committee of Basel approved the study, and it was performed in accordance with the ethical standards laid down in the Declaration of Helsinki. Parents gave written informed consent for the children to participate and assent was obtained from the children.

Procedure and Measures

A portable GAITRite electronic walkway system (GAITRite Platinum; CIR Systems, Sparta, New Jersey) was used for gait assessment. This system consists of a 7.01-m-long electronic mat with 23 040 integrated pressure sensors. Electronically inactive sections with a length of 1.25 m were added on each end of the system to minimize the effects of acceleration and deceleration. The reliability and validity of children's gait assessment using GAITRite is well established [54], [55]. Analyses were performed according to the European guidelines for spatiotemporal gait analysis [56]. The following spatio-temporal gait parameters were derived: gait velocity (cm/s) which is considered a marker of general functional performance [40] and is the most common reported gait parameter; cadence, measured as steps per minute; stride length (cm) which is the distance between the heel points of two consecutive footfalls of the same foot; single support time (s) which is the time elapsed between the last contact of the current footfall and the initial contact of the next footfall of the same foot; double support time (s) which is the time when both feet are on the floor. In order to account for differences in height of the children we additionally normalized gait velocity, cadence, and stride length to dimensionless

quantities using the formulas:

$$\text{Normalized velocity} = \frac{\text{gait velocity}}{\sqrt{(g \times l)}}$$

$$\text{Normalized cadence} = \frac{\text{cadence}}{\sqrt{(g/l)}}$$

$$\text{Normalized stride length} = \frac{\text{stride length}}{l}$$

where g is the gravitational constant (9.81 m/s^2) and l is leg length [57], [58]. Finally, we measured gait variability, assessed as variability in stride velocity and stride length using the percentage coefficient of variation (standard deviation/mean $\times 100$). Gait variability is sensitive to more subtle physiological changes and is considered to reflect the regularity, rhythmicity, and automaticity of gait [25]. Correlations between gait parameters in single-task walking are shown in Table 2 and comparable to the correlations in dual- and triple-task conditions (data not shown).

Prior to gait assessment children were asked to complete all concurrent tasks for 10 s while standing. Concurrent tasks were selected according to related dual-task research and were (1) naming animals at self-selected speed and rhythm (animals) [59], [60]; (2) listening to and memorizing digits (digits) [61], [62], where children heard a word list comprising five digits and five objects as distractors presented in randomized order from a computer over loudspeakers, installed at the front left and right corner of the laboratory. Afterward, the children were asked to recall the digits; (3) carrying a tray ($45 \times 30 \text{ cm}$) loaded with 7 table tennis balls (tray)

Table 2. Correlations between gait parameters in single-task walking ($N = 88$).

	Gait velocity	Cadence	Stride length	Single support time	Double support time	Normalized velocity	Normalized cadence	Normalized stride length	Stride velocity variability
1 Gait velocity	1								
2 Cadence	.363**	1							
3 Stride length	.733***	.038	1						
4 Single support time	-.312**	-.953***	-.037	1					
5 Double support time	-.666***	-.477***	-.141	.388***	1				
6 Normalized velocity	.932***	.412***	.525***	-.361**	-.784***	1			
7 Normalized cadence	.802***	.423***	.332**	-.346**	-.662***	.709***	1		
8 Normalized stride length	.614***	.215*	.452***	-.209	-.536***	.790***	.132	1	
9 Stride velocity variability	-.349**	-.044	-.394***	.050	.093	-.283**	-.200	-.234*	1
10 Stride length variability	-.388***	-.008	-.466***	.016	.087	-.309**	-.199	-.275*	.675***

* $p < .05$

** $p < .01$

*** $p < .001$

doi:10.1371/journal.pone.0144363.t002

[45], [63], [64]. The performance on this task was assessed as number of fallen balls while walking; and (4) unfastening and fastening a button [65], [66] having a diameter of 1 cm (button).

To familiarize the children with the walkway system, each child was given one demonstration and one practice trial before the recordings. A walk was approximately 10 m long and comprised 4 to 5 strides. Then, children were instructed to walk at their normal pace (single-task condition) in four trials. For each child gait parameters were averaged over the trials for further data analyses. Afterward, the children were instructed to walk at their normal pace and simultaneously perform a concurrent task (4 dual-task conditions) or 2 concurrent tasks (3 triple-task conditions) with 1 trial each. While triple-task walking, the children were asked to (1) name animals and carry a tray with balls (animals/tray); (2) listen to and memorize digits and carry a tray with balls (digits/tray) and; (3) listen to and memorize digits and unfasten and fasten a button (digits/button).

We defined "single tasks" as performing only one task at a time (i.e. walking without concurrent tasks or performing a concurrent task without walking). "Dual tasks" were defined as performing two tasks at a time (i.e. walking and one concurrent task such as naming animals), while "triple tasks" were defined as performing three tasks at a time (i.e. walking and two concurrent tasks such as naming animals and carrying a tray). In the dual- and triple-task conditions children were not instructed to prioritize any of the tasks. Task order was not randomized across the study. No randomization was conducted to avoid that some of the children had to perform the same concurrent task in an immediate sequence. Consecutive performance of the same concurrent task (e.g. naming animals) could have led to enhanced learning and memorizing effects in these children.

Statistical Analysis

First, group differences in gait parameters in the single-task condition were assessed for spatiotemporal gait parameters, normalized gait parameters, and gait variability measures using multivariate analysis of variance (MANOVA). Second, effects of dual- and triple-task conditions on gait were examined using repeated-measures MANOVAs with 3 between-subjects factors (prematurity status: preterm ≤ 1500 g, preterm > 1500 g, full-term) and 8 within-subject factors (walking condition: one single-task, four dual-tasks, three triple-tasks) for each gait parameter. Significant effects were followed up with Bonferroni corrected post-hoc pairwise comparisons in which we focused on single-task versus dual- and triple-task comparisons. Additionally, tests for linear trend by polynomial linear contrast analysis were conducted to test for gait alterations across preterm children with birth weight ≤ 1500 g, preterm children with birth weight > 1500 g, and full-term children. Extreme values in gait parameters defined as a z score exceeding 3 SDs from the mean were truncated to ± 3 SD.

Third, a MANOVA was performed to assess group differences in concurrent task performance during single-task condition and, finally, repeated-measures MANOVAs were conducted to examine the effects of dual- and triple-task conditions on the concurrent tasks. Significant effects were followed up with Bonferroni corrected post-hoc pairwise comparisons in which we focused on single-task versus dual- and triple-task comparisons. Tests for linear trend by polynomial linear contrast analysis were employed to test for alterations in concurrent task performance across preterm children with birth weight ≤ 1500 g, preterm children with birth weight > 1500 g, and full-term children.

The normality of distributions of the data was assessed using the Kolmogorov-Smirnov test. As parameters of double support time, gait variability and concurrent task performance were not normally distributed, they were log-transformed. The level of significance was set to .05, with $p < .10$ considered a tendency. The F statistic, p values (two-tailed), and effect sizes (η^2) are reported.

Results

For spatio-temporal gait parameters, means and standard deviations in single-, dual-, and triple-task conditions are shown in Table 3. In the single-task condition the MANOVA showed no significant group differences in these gait parameters (Wilks' multivariate test, $F(10,162) = 0.870$, $p = .563$, $\eta^2 = 0.051$). Repeated-measures MANOVAs revealed a significant within-subject effect of walking condition on each spatio-temporal gait parameter (Wilks' multivariate test, $F(7,73) = 22.983$ to 103.825 , $p < .001$, $\eta^2 = 0.691$ to 0.909). Pairwise comparisons revealed lower gait velocity, lower cadence, lower stride length as well as higher single support time and higher double support time in dual- and triple-task conditions compared to single-task walking ($p < .01$) with exception of the dual-task condition button in which children showed comparable single support time compared to single-task walking. There were no significant main effects of prematurity status or Walking Condition \times Prematurity Status interactions.

For normalized gait parameters, means and standard deviations in single-, dual-, and triple-task conditions are shown in Table 4. In the single-task condition the MANOVA showed no significant group differences in these gait parameters (Wilks' multivariate test, $F(6,166) = 0.692$, $p = .656$, $\eta^2 = 0.024$). Repeated-measures MANOVAs revealed a significant within-subject effect of walking condition on each normalized gait parameter (Wilks' multivariate test, $F(7,73) = 37.336$ to 95.504 , $p < .001$, $\eta^2 = 0.784$ to 0.902). Pairwise comparisons revealed lower normalized velocity, lower normalized cadence, and lower normalized stride length in dual- and triple-task conditions compared to single-task walking ($p < .001$). There were no significant main effects of prematurity status or Walking Condition \times Prematurity Status interactions.

Table 5 shows means and standard deviations of gait variability measures in single-, dual-, and triple-task conditions. In the single-task condition the MANOVA showed no significant group differences in the gait variability parameters (Wilks' multivariate test, $F(4,168) = 0.599$, $p = .664$, $\eta^2 = 0.014$). Statistical results from the repeated-measures MANOVAs for each gait parameter are presented in Table 6. For gait variability, results revealed a significant within-subject effect of walking condition on stride velocity variability (Wilks' multivariate test, $F(7,72) = 30.200$, $p < .001$, $\eta^2 = 0.746$) and stride length variability (Wilks' multivariate test, $F(7,72) = 19.003$, $p < .001$, $\eta^2 = 0.649$). Pairwise comparisons revealed higher stride velocity variability and higher stride length variability in dual- and triple-task conditions compared to single-task walking ($p < .05$) with exception of the dual-task condition digits in which children showed comparable stride length variability compared to single-task walking.

For stride velocity variability there was a tendency for a between-subjects effect of prematurity status, $F(2,78) = 3.021$, $p = .088$, $\eta^2 = 0.060$, with post-hoc comparisons showing that preterm children with birth weight ≤ 1500 g walked with marginally significantly higher gait variability compared to controls ($p = .084$). Additionally, polynomial contrasts revealed a linear trend across all walking conditions ($p = .028$), indicating systematically decreasing gait variability from preterm children with birth weight ≤ 1500 g to preterm children with birth weight > 1500 g to full-term children. The significance of this multivariate linear trend was driven by univariate linear trends in the walking conditions digits ($p = .069$), digits/tray ($p = .035$), and digits/button ($p = .044$), as shown in Fig 1. There were no significant Walking Condition \times Prematurity Status interactions.

Means and standard errors for task performance in single-, dual- and triple-task conditions are shown in Fig 2. As both groups of children showed no variance in the tray concurrent task, it was excluded from further analyses. In single-task conditions the MANOVA revealed a significant effect of prematurity status (Wilks' multivariate test, $F(6,148) = 2.473$, $p = .026$, $\eta^2 = 0.091$). Follow-up univariate tests showed a significant group difference for animals ($F(2,76) =$

Table 3. Means (and standard deviations) of spatio-temporal gait parameters for preterm and full-term children in single-, dual-, and triple-task conditions.

Gait parameters	Preterm		Full Term (N = 44)
	≤1500g (n = 20)	>1500g (n = 24)	
Gait velocity (cm/s)			
Single-task walking	126.61 (15.08)	137.05 (16.73)	132.31 (17.46)
Dual-task walking			
Animals	100.13 (21.18)	102.76 (21.76)	96.87 (20.25)
Digits	97.52 (23.00)	101.30 (15.04)	101.86 (20.25)
Tray	92.93 (21.79)	96.36 (19.31)	100.38 (22.77)
Button	77.84 (20.11)	80.89 (18.30)	82.03 (17.06)
Triple-task walking			
Animals/Tray	81.37 (20.13)	85.04 (19.74)	83.43 (19.84)
Digits/Tray	88.89 (21.10)	90.37 (22.28)	96.30 (16.42)
Digits/Button	86.08 (19.38)	89.20 (16.77)	86.80 (20.32)
Cadence (steps/min)			
Single-task walking	124.15 (11.12)	122.08 (10.09)	124.22 (11.37)
Dual-task walking			
Animals	107.40 (15.33)	105.51 (19.01)	105.79 (16.70)
Digits	109.60 (14.09)	107.75 (14.30)	112.83 (10.86)
Tray	112.28 (12.71)	111.92 (13.70)	116.64 (14.04)
Button	100.64 (13.41)	96.20 (11.50)	102.38 (12.56)
Triple-task walking			
Animals/Tray	107.97 (14.17)	101.85 (13.51)	110.68 (11.82)
Digits/Tray	105.28 (15.44)	100.47 (14.23)	104.66 (14.59)
Digits/Button	108.48 (14.68)	106.67 (14.21)	109.40 (14.37)
Stride length (cm)			
Single-task walking	125.47 (8.62)	131.95 (12.48)	127.91 (12.21)
Dual-task walking			
Animals	114.88 (14.96)	114.91 (17.41)	110.35 (12.67)
Digits	108.11 (11.19)	111.16 (10.42)	108.41 (11.45)
Tray	100.88 (16.52)	101.47 (16.46)	103.10 (18.24)
Button	95.44 (13.37)	96.86 (14.41)	95.74 (13.23)
Triple-task walking			
Animals/Tray	95.58 (13.37)	97.69 (13.97)	95.35 (15.77)
Digits/Tray	97.35 (11.37)	98.01 (13.07)	94.59 (15.82)
Digits/Button	102.77 (13.17)	101.26 (16.12)	104.33 (12.44)
Single support time (s)			
Single-task walking	0.39 (0.03)	0.40 (0.03)	0.39 (0.03)
Dual-task walking			
Animals	0.43 (0.04)	0.47 (0.10)	0.45 (0.09)
Digits	0.43 (0.04)	0.44 (0.05)	0.41 (0.03)
Tray	0.45 (0.04)	0.47 (0.05)	0.44 (0.05)
Button	0.40 (0.03)	0.41 (0.04)	0.39 (0.04)
Triple-task walking			
Animals/Tray	0.42 (0.04)	0.45 (0.06)	0.41 (0.04)
Digits/Tray	0.43 (0.05)	0.44 (0.05)	0.42 (0.04)
Digits/Button	0.41 (0.04)	0.42 (0.05)	0.40 (0.04)

(Continued)

Table 3. (Continued)

Gait parameters	Preterm		Full Term (N = 44)
	≤1500g (n = 20)	>1500g (n = 24)	
Double support time (s)			
Single-task walking	0.19 (0.03)	0.18 (0.03)	0.19 (0.03)
Dual-task walking			
Animals	0.25 (0.06)	0.25 (0.07)	0.26 (0.07)
Digits	0.26 (0.07)	0.25 (0.05)	0.25 (0.04)
Tray	0.28 (0.07)	0.27 (0.08)	0.26 (0.07)
Button	0.33 (0.08)	0.33 (0.09)	0.31 (0.07)
Triple-task walking			
Animals/Tray	0.32 (0.09)	0.31 (0.09)	0.31 (0.08)
Digits/Tray	0.31 (0.09)	0.29 (0.08)	0.30 (0.08)
Digits/Button	0.29 (0.07)	0.30 (0.08)	0.27 (0.06)

Note. Animals = naming animals; Digits = listening to and memorizing digits; Tray = carrying a tray with table tennis balls; Button = unfastening and fastening a button.

doi:10.1371/journal.pone.0144363.t003

6.277, $p = .003$, $\eta^2 = 0.142$). Post-hoc pairwise tests showed that preterm children with birth weight ≤ 1500 g named fewer animals than controls ($p = .004$). Additionally, the test for linear trend was significant, indicating systematically increasing task performance from preterm children with birth weight ≤ 1500 g to preterm children with birth weight > 1500 g to full-term children ($p = .001$).

Repeated-measures MANOVAs revealed a significant within-subject effect of walking condition on naming animals (Wilks' multivariate test, $F(2,83) = 46.299$, $p < .001$, $\eta^2 = 0.527$). Pairwise comparisons showed that children named fewer animals in the triple-task condition compared to single-task walking ($p < .001$). There was no main effect of prematurity status nor a significant Walking Condition \times Prematurity Status interaction.

Further, there was a significant within-subject effect of walking condition on listening to and memorizing digits (Wilks' multivariate test, $F(3,64) = 16.033$, $p < .001$, $\eta^2 = 0.429$). Pairwise comparisons showed that children recalled fewer digits in the triple-task conditions compared to single-task walking ($p < .01$). There was no main effect of prematurity status nor a significant Walking Condition \times Prematurity Status interaction.

Finally, there was a significant within-subject effect of walking condition on unfastening and fastening a button (Wilks' multivariate test, $F(2,80) = 7.341$, $p = .001$, $\eta^2 = 0.155$). Pairwise comparisons showed that in the triple-task condition children unfastened and fastened a button less often than in single-task walking ($p < .05$). There was no main effect of prematurity status nor a significant Walking Condition \times Prematurity Status interaction.

Discussion

In everyday life children often do things concomitantly with walking, such as fastening jacket buttons or listening to someone talking, which results in less attention that can be directed to the control of gait. As very preterm children show deficits in executive and attentional functions, the aim of the study was to investigate for the first time gait alterations in dual- and triple-task conditions in very preterm and full-term children during middle childhood.

Our results are consistent with the notion that gait requires executive and attentional functions in children [44–46]: Concurrent information processing in dual- and triple-task

Table 4. Means (and standard deviations) of normalized gait parameters for preterm and full-term children in single-, dual-, and triple-task conditions.

Gait parameters	Preterm		Full Term (N = 44)
	≤1500g (n = 20)	>1500g (n = 24)	
Normalized velocity			
Single-task walking	0.47 (0.06)	0.51 (0.07)	0.50 (0.07)
Dual-task walking			
Animals	0.37 (0.08)	0.38 (0.08)	0.36 (0.08)
Digits	0.36 (0.09)	0.38 (0.06)	0.38 (0.06)
Tray	0.35 (0.08)	0.36 (0.07)	0.38 (0.08)
Button	0.29 (0.07)	0.30 (0.06)	0.31 (0.06)
Triple-task walking			
Animals/Tray	0.30 (0.07)	0.31 (0.07)	0.31 (0.08)
Digits/Tray	0.33 (0.08)	0.33 (0.08)	0.36 (0.06)
Digits/Button	0.32 (0.07)	0.33 (0.06)	0.32 (0.08)
Normalized cadence			
Single-task walking	0.55 (0.05)	0.57 (0.04)	0.56 (0.05)
Dual-task walking			
Animals	0.48 (0.08)	0.49 (0.08)	0.48 (0.07)
Digits	0.49 (0.08)	0.50 (0.05)	0.51 (0.04)
Tray	0.50 (0.06)	0.52 (0.06)	0.53 (0.06)
Button	0.44 (0.06)	0.46 (0.06)	0.46 (0.06)
Triple-task walking			
Animals/Tray	0.46 (0.07)	0.48 (0.07)	0.47 (0.07)
Digits/Tray	0.48 (0.07)	0.50 (0.06)	0.49 (0.06)
Digits/Button	0.47 (0.07)	0.49 (0.07)	0.50 (0.05)
Normalized stride length			
Single-task walking	1.72 (0.16)	1.79 (0.18)	1.77 (0.17)
Dual-task walking			
Animals	1.57 (0.22)	1.55 (0.20)	1.53 (0.20)
Digits	1.48 (0.16)	1.50 (0.13)	1.50 (0.16)
Tray	1.37 (0.18)	1.37 (0.19)	1.42 (0.20)
Button	1.30 (0.21)	1.31 (0.16)	1.33 (0.16)
Triple-task walking			
Animals/Tray	1.31 (0.17)	1.31 (0.16)	1.32 (0.21)
Digits/Tray	1.33 (0.13)	1.32 (0.16)	1.30 (0.20)
Digits/Button	1.40 (0.15)	1.36 (0.18)	1.44 (0.16)

Note. Animals = naming animals; Digits = listening to and memorizing digits; Tray = carrying a tray with table tennis balls; Button = unfastening and fastening a button.

doi:10.1371/journal.pone.0144363.t004

conditions interfered with gait, leading to lower gait velocity, lower stride length and higher gait variability compared to single-task walking in both preterm and full-term children.

Regarding prematurity status the results showed systematic decreases in stride velocity variability from preterm children with birth weight ≤ 1500 g to preterm children with birth weight > 1500 g to full-term children, which is in line with research showing that motor impairments occur more frequently in preterm children who were less mature at birth [7], [67]. No significant group differences, however, were revealed in spatio-temporal gait parameters, normalized gait parameters or stride length variability. The result that there were

Table 5. Means (and standard deviations) of gait variability parameters for preterm and full-term children in single-, dual-, and triple-task conditions.

Gait parameters	Preterm		Full Term (N = 44)
	≤1500g (n = 20)	>1500g (n = 24)	
Velocity variability			
Single-task walking	2.81 (0.89)	2.88 (1.11)	2.59 (0.82)
Dual-task walking			
Animals	6.63 (4.36)	8.43 (7.41)	8.15 (7.31)
Digits	4.58 (2.04)	4.37 (2.35)	3.63 (1.55)
Tray	6.39 (3.48)	5.60 (3.40)	6.06 (3.09)
Button	6.78 (5.01)	6.58 (4.70)	5.34 (2.46)
Triple-task walking			
Animals/Tray	5.82 (2.47)	6.46 (4.37)	6.84 (4.71)
Digits/Tray	6.85 (4.24)	5.44 (4.10)	4.91 (2.96)
Digits/Button	5.71 (3.45)	5.33 (4.01)	3.99 (2.28)
Stride length variability			
Single-task walking	2.22 (0.70)	2.15 (0.79)	1.99 (0.69)
Dual-task walking			
Animals	4.37 (3.36)	4.81 (4.32)	5.00 (3.91)
Digits	2.58 (1.12)	2.62 (1.53)	2.24 (1.11)
Tray	3.92 (2.59)	4.25 (3.90)	4.67 (2.40)
Button	4.55 (3.42)	4.75 (3.90)	3.64 (1.67)
Triple-task walking			
Animals/Tray	3.70 (1.62)	4.38 (2.72)	4.36 (2.94)
Digits/Tray	3.73 (2.28)	4.10 (2.77)	3.54 (2.07)
Digits/Button	3.66 (2.06)	3.87 (2.94)	2.60 (1.44)

Note. Animals = naming animals; Digits = listening to and memorizing digits; Tray = carrying a tray with table tennis balls; Button = unfastening and fastening a button.

doi:10.1371/journal.pone.0144363.t005

significant group differences in gait variability but not in gait velocity is in line with the notion that gait variability may provide a more discriminant and sensitive measure of gait than other gait variables [25].

Higher gait variability is also present in individuals who exhibit impairments in executive and attentional functions [25], [36], [41–43]. Therefore, deficits in executive and attentional functions in preterm children [3–5] may contribute to the alterations in stride velocity variability in preterm children found in this study. However, the underlying mechanisms for dual task interference in preterm children are not clear. In accordance with the capacity-sharing theory [68] it may be possible that more limited attentional resources in preterm compared to full-term children [69] lead to impaired gait or concurrent task performance as soon as the demands on attention exceed a certain threshold. On the other hand it might be possible that preterm children have more difficulties in switching from one task to the other compared to full-term children [69], which may lead to diminished performance in one or both of the tasks. This notion is derived from the bottleneck theory [70] proposing that two simultaneously performed tasks are cognitively processed sequentially which poses high demands on the capacity to switch between tasks.

In the present study stride velocity variability increased with decreasing maturity of the children at birth, which was most apparent in conditions in which the children had to listen to and

Table 6. Statistical results from the repeated-measures MANOVAs comparing the single- to the dual- and triple-task conditions for each gait parameter.

Gait parameter	Walking condition			Prematurity status			Walking condition x Prematurity status		
	F	p	η^2	F	p	η^2	F	p	η^2
Spatio-temporal									
Gait velocity	80.039	< .001	.885	0.973	.383	.024	0.697	.774	.063
Cadence	35.653	< .001	.774	1.133	.327	.028	0.865	.598	.077
Stride length	103.825	< .001	.909	0.359	.700	.009	1.186	.292	.102
Single support time	22.983	< .001	.691	2.265	.111	.055	1.507	.115	.128
Double support time	50.999	< .001	.832	0.599	.552	.015	0.878	.584	.079
Normalized									
Velocity	76.647	< .001	.880	0.961	.387	.024	0.697	.774	.063
Cadence	37.936	< .001	.784	1.183	.312	.029	0.635	.832	.057
Stride length	95.504	< .001	.902	0.275	.761	.007	1.277	.228	.109
Variability									
Stride velocity	30.200	< .001	.746	2.511	.088	.060	0.890	.570	.080
Stride length	19.003	< .001	.649	0.597	.553	.015	1.058	.400	.093

doi:10.1371/journal.pone.0144363.t006

memorize digits. This finding appears consistent with results from Huang et al. [46] who found that a concurrent auditory task showed the largest interference effect on gait in five- to seven-year-old children. These authors' interpretation of their findings was that it is particularly difficult to walk and concurrently perform a task requiring continuous processing of new auditory information. Regarding concurrent task performance, the concurrent performance in naming animals was also related to birth weight such that there was a systematic increase in the number of named animals from preterm children with birth weight ≤ 1500 g to preterm children with birth weight > 1500 g to full-term children, what is in line with previous research [1]. Further, preterm children named fewer animals than full-term children while single tasking. This is in accordance with previous research showing that preterm children scored lower than full-term children in word fluency tests, which are an established measure of executive function [6]. Moreover, it is in line with a recent study showing that the gap in cognitive performance of preterm compared to full-term children systematically increased with increasing cognitive workload of the tasks [71].

However, it remains to be determined why effects of prematurity status were particularly apparent in auditory and verbal fluency conditions. One possible explanation may lie in preterm children's alterations of interhemispheric integration. Recently, Belmonti, Berthoz, Cioni, Fiori and Guzzetta [72] studied 22 children with cerebral palsy of which 10 children were born premature. In these children locomotor navigation was affected by lesions involving the right frontal lobes, indicating that spatial memory in navigation might depend on right-lateralized networks. Further, there is evidence that cerebral connectivity is altered in auditory language functions in preterm children [73]. Therefore, it is of interest for future studies if such alterations in connectivity in preterm children are also evident in locomotor navigation tasks as they might underlie preterm children's difficulties in walking and concurrently performing an auditory or a verbal fluency task.

From studies with elderly individuals it is known that particularly increased gait variability is associated with a higher risk of falling [34]. However, we are not aware of studies that have examined associations between gait variability and accidents or physical activity in childhood and adolescence. On the other hand, there is evidence that preterm children are less physically

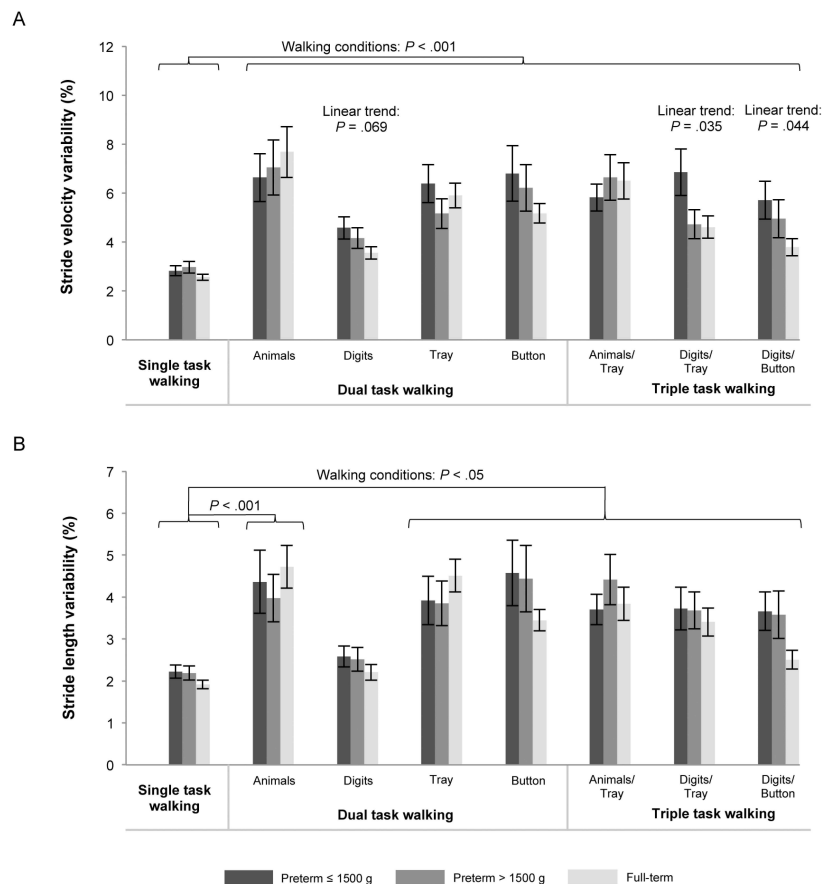


Fig 1. Means and standard errors for gait variability including stride velocity variability (A) and stride length variability (B) for preterm children with birth weight ≤ 1500 g and > 1500 g, and full-term children in single-, dual-, and triple-task conditions. Concurrent tasks were naming animals (animals), listening to and memorizing digits (digits), carrying a tray with table tennis balls (tray), and unfastening and fastening a button (button). P values are presented for significant main effects of walking conditions (comparing single task vs. dual and triple tasks) and for linear trends showing increasing gait performance from preterm children with birth weight ≤ 1500 g to preterm children with birth weight > 1500 g to full-term children. For statistical analyses log-transformed parameters of gait variability were used.

doi:10.1371/journal.pone.0144363.g001

active and participate less often in organized sports from childhood through young adulthood [30–35], which may increase their risk for poor cardiovascular outcomes in later life [33]. It is possible that organized sports provide less reinforcing experiences for preterm children due to their more limited walking performance, which may eventually direct them toward less physically active leisure activities. However, the error variance within the assessed groups was high and effect sizes for group differences between preterm and full-term children were small and not consistent across all gait parameters. Therefore, it remains to be shown in future research

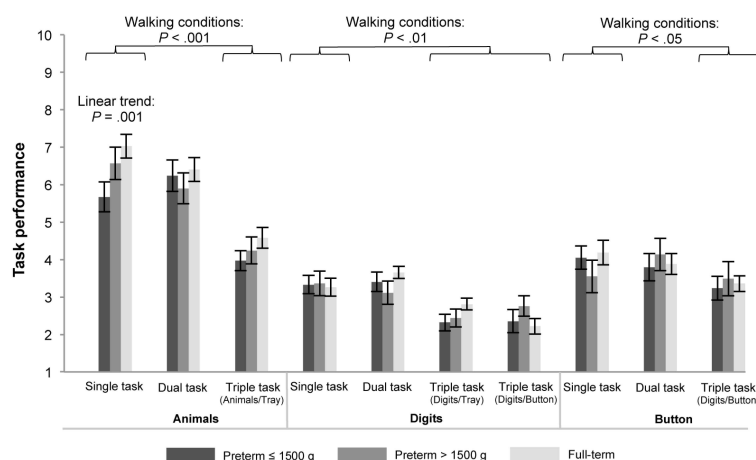


Fig 2. Means and standard errors for task performance for preterm children with birth weight ≤ 1500 g and > 1500 g, and full-term children in single-, dual-, and triple-task conditions. Measures were number of named animals (animals), recalled digits (digits), and how many times a button could be unfastened and fastened (button). Performance in the tray concurrent task was excluded from the figure as both groups showed no variance in this task. *P* values are presented for significant main effects of walking conditions (comparing single task vs. dual- and triple tasks) and for linear trends showing increasing gait performance from preterm children with birth weight ≤ 1500 g to preterm children with birth weight > 1500 g to full-term children. For statistical analyses log-transformed parameters of task performance were used.

doi:10.1371/journal.pone.0144363.g002

whether the small differences in gait patterns between preterm and full-term children are meaningful for everyday life and associated with other aspects of children's development.

Our study has strengths and limitations. We consider it a strength of this study that gait was assessed using an objective electronic gait assessment system with proven reliability and validity [54], [55] for gait assessment when children are wearing their normal clothes and shoes, making it possible to assess children's gait as it is exhibited in their everyday lives. However, the number of walks per condition was limited and increasing the number of walks might have increased reliability of gait measures. Therefore, replication in other samples of preterm children is important to exclude the possibility that the significant group differences found in the present study were due to the limited number of walks. Further, we analyzed spatio-temporal, normalized, and variability measures of straight walking as the walkway system used in our study did not allow the capture of gait kinematics [74] or the assessment of curvilinear walking [24]. Preterm children participating in our study had higher birth weight and gestational age than nonparticipants, which may lead to underestimation of the effects of dual and triple tasking on gait as cognitive and motor deficits are more profound in less maturely born preterm children [7], [67]. Finally, the cross-sectional design precludes the identification of developmental changes. A longitudinal research approach may be taken to examine whether the gait alterations in very preterm children have to be seen as maturational delay, i.e. that gait matures later in preterm compared to full-term children, or rather as a persistent deviance from the gait pattern of full-term children, i.e. that preterm children do not achieve the maturation of full-term children. In this line, it has been suggested that poorer performance in executive functions of preterm compared to full-term children might reflect a developmental delay rather than a deviance [75].

Conclusion

Results of this study support the role of executive and attentional functions in the control of gait. Further, the results of our study indicate that preterm children who were less mature at birth walk with higher stride velocity variability. The relevance of these results for everyday motor activity of preterm children as well as whether early developmental intervention training programs focusing on executive function and/or motor behavior [76] could improve gait of preterm children should be the topic of further studies.

Supporting Information

S1 Dataset. Data set used in this study.
(SAV)

Author Contributions

Conceived and designed the experiments: PH OM NP AG SL. Performed the experiments: PH OM NP. Analyzed the data: PH OM NP PW AG SL. Contributed reagents/materials/analysis tools: PH OM NP PW AG SL. Wrote the paper: PH OM NP PW AG SL.

References

1. Saigal S, Doyle LW. An overview of mortality and sequelae of preterm birth from infancy to adulthood. *Lancet*. 2008; 371: 261–269. doi: [10.1016/S0140-6736\(08\)60136-1](https://doi.org/10.1016/S0140-6736(08)60136-1) PMID: 18207020
2. Lemola S. Long-term outcomes of very preterm birth. Mechanisms and interventions. *Eur Psychol*. 2015; 20: 128–137. doi: [10.1027/1016-9040/a000207](https://doi.org/10.1027/1016-9040/a000207)
3. Aarnoudse-Moens CSH, Weisglas-Kuperus N, van Goudoever JB, Oosterlaan J. Meta-analysis of neurobehavioral outcomes in very preterm and/or very low birth weight children. *Pediatrics*. 2009; 124: 717–728. doi: [10.1542/peds.2008-2816](https://doi.org/10.1542/peds.2008-2816) PMID: 19651588
4. Mulder H, Pitchford NJ, Hagger MS, Marlow N. Development of executive function and attention in preterm children: a systematic review. *Dev Neuropsychol*. 2009; 34: 393–421. doi: [10.1080/87565640902964524](https://doi.org/10.1080/87565640902964524) PMID: 20183707
5. Hagmann-von Arx P, Perkinson-Gloor N, Brand S, Albert D, Holsboer-Trachsler E, Grob A, Weber P, Lemola S. In school-age children who were born very preterm sleep efficiency is associated with cognitive function. *Neuropsychobiology*. 2014; 70: 244–252. doi: [10.1159/000369026](https://doi.org/10.1159/000369026) PMID: 25720547
6. Goyen TA, Lui K. Developmental coordination disorder in “apparently normal” school children born extremely preterm. *Arch Dis Child*. 2009; 94: 298–302. doi: [10.1136/adc.2007.134692](https://doi.org/10.1136/adc.2007.134692) PMID: 18838419
7. De Kievit JF, Piek JP, Aarnoudse-Moens CS, Oosterlaan J. Motor development in very preterm and very low-birth-weight children from birth to adolescence. *JAMA*. 2009; 302: 2235–2242. doi: [10.1001/jama.2009.1708](https://doi.org/10.1001/jama.2009.1708) PMID: 19934425
8. Piek JP, Baynam GB, Barrett NC. The relationship between fine and gross motor ability, self-perception and self-worth in children and adolescents. *Hum Movement Sci*. 2006; 25: 65–75. doi: [10.1016/j.humov.2005.10.011](https://doi.org/10.1016/j.humov.2005.10.011)
9. Cantell M, Smyth M, Ahonen T. Clumsiness in adolescence: educational, motor, and social outcomes of motor delay detected at 5 years. *Adapt Phys Activ Q*. 1994; 11: 115–129.
10. Piek JP, Dworcan M, Barret N, Coleman R. Determinants of self-worth in children with developmental coordination disorder. *Dev Med Child Neur*. 2000; 37: 976–984. doi: [10.1080/713671115](https://doi.org/10.1080/713671115)
11. Schoemaker MM, Kalverboer AF. Social and affective problems of children who are clumsy: how early do they begin. *Adapt Phys Activ Q*. 2004; 11: 130–140.
12. Skinner RA, Piek JP. Psychosocial implications of poor motor coordination in children and adolescents. *Hum Mov Sci*. 2001; 20: 73–94. doi: [10.1016/S0167-9457\(01\)00029-X](https://doi.org/10.1016/S0167-9457(01)00029-X) PMID: 11471399
13. Bouffard M, Watkinson EJ, Thompson LP, Causgrove Dunn JL, Romanow SKE. (1996). A test of the activity deficit hypothesis with children with movement difficulties. *Adapt Phys Activ Q*. 1996; 13: 61–73.
14. Bejerot S, Humble MB. Childhood clumsiness and peer victimization: A case-control study of psychiatric patients. *BMC Psychiatry*. 2013; 13: 68. doi: [10.1186/1471-244X-13-68](https://doi.org/10.1186/1471-244X-13-68) PMID: 23442984

15. Bejerot S, Plenty S, Humble A, Humble MB. Poor motor skills: A risk marker for bully victimization. *Aggressive Behav.* 2013; 39: 453–461. doi: [10.1002/ab.21489](#)
16. Piek JP, Barrett NC, Allen LSR, Jones A, Louise M. The relationship between bullying and self-worth in children with movement coordination problems. *Br J Educ Psychol.* 2005; 75: 453–463. doi: [10.1348/000709904X24573](#) PMID: [16238876](#)
17. Zwicker JG, Missiuna C, Harris SR, Boyd LA. Developmental coordination disorder: A review and update. *Europ J Paediatr Neuro.* 2012; 16: 573–581. doi: [10.1016/j.ejpn.2012.05.005](#)
18. Adolph KE, Vereijken B, Shrout PE. What changes in infant walking and why. *Child Dev.* 2003; 74: 475–497. doi: [10.1111/1467-8624.7402011](#) PMID: [12705568](#)
19. Hausdorff JM. Gait dynamics, fractals and falls: finding meaning in the stride-to-stride fluctuations of human walking. *Hum Mov Sci.* 2007; 26: 555–589. doi: [10.1016/j.humov.2007.05.003](#) PMID: [17618701](#)
20. Storvold GV, Aarethun K, Bratberg GH. Age for onset of walking and prewalking strategies. *Early Human Dev.* 2013; 89: 655–659. doi: [10.1016/j.earlhumdev.2013.04.010](#)
21. Jeng SF, Hua-Fang L, Jin-Shin L, Jia-Woei H. Optimization of walking in children. *Med Sci Sports.* 1997; 29: 370–376. doi: [10.1097/00005768-199703000-00012](#)
22. Hausdorff JM, Zemany L, Peng CK, Goldberger AL. Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children. *J Appl Physiol.* 1999; 86: 1040–1047. PMID: [10066721](#)
23. Lythgo N, Wilson C, Gaele M. Basic gait and symmetry measures for primary school-aged children and young adults whilst walking barefoot and with shoes. *Gait Posture.* 2009; 30: 502–506. doi: [10.1016/j.gaitpost.2009.07.119](#) PMID: [19692245](#)
24. Belmonti V, Cioni G, Berthoz A. Development of anticipatory orienting strategies and trajectory formation in goal-oriented locomotion. *Exp Brain Res.* 2013; 227: 131–147. doi: [10.1007/s00221-013-3495-3](#) PMID: [23588420](#)
25. Hausdorff JM. Gait variability: methods, modeling and meaning. *J Neuroeng Rehabil.* 2005; 2: 19. doi: [10.1186/1743-0003-2-19](#) PMID: [16033650](#)
26. Jeng SF, Lau TW, Hsieh WS, Luo HJ, Chen PS, Lin KW et al. Development of walking in preterm and term infants: age of onset, qualitative features and sensitivity to resonance. *Gait Posture.* 2008; 27: 340–346. doi: [10.1016/j.gaitpost.2007.04.012](#) PMID: [17532638](#)
27. Nuysink J, van Haastert IC, Eijssermans MJC, Koopman-Esseboom C, Helders PJM, de Vries LS et al. Prediction of gross motor development and independent walking in infants born very preterm using the Test of Infant Motor Performance and the Alberta Infant Motor Scale. *Early Hum Dev.* 2013; 89: 693–697. doi: [10.1016/j.earlhumdev.2013.04.016](#) PMID: [23712056](#)
28. Marin Gabriel MA, Pallas Alonso CR, De La Cruz Bertolo J, Caserio Carbonero S, Lopez Maestro M, Moral Pumarega M et al. Age of sitting unsupported and independent walking in very low birth weight preterm infants with normal motor development at 2 years. *Acta Paediatr.* 2009; 98: 1815–1821. doi: [10.1111/j.1651-2227.2009.01475.x](#) PMID: [19807707](#)
29. Marlow N, Hennessy EM, Bracewell MA, Wolke D. Motor and executive function at 6 years of age after extremely preterm birth. *Pediatrics.* 2007; 120: 793–803. doi: [10.1542/peds.2007-0440](#) PMID: [17908767](#)
30. Rogers M, Fay TB, Whitfield MF, Tomlinson J, Grunau RE. Aerobic capacity, strength, flexibility, and activity level in unimpaired extremely low birth weight (≤ 800 g) survivors at 17 years of age compared with term-born control subjects. *Pediatrics.* 2005; 116: e58. doi: [10.1542/peds.2004-1603](#) PMID: [15997047](#)
31. Clemm H, Roksund O, Thorsen E, Eide GE, Markestad T, Halvorsen T. Aerobic capacity and exercise performance in young people born extremely preterm. *Pediatrics.* 2012; 129: e97–e105. doi: [10.1542/peds.2011-0326](#) PMID: [22201154](#)
32. Finn K, Johannsen N, Specker B. Factors associated with physical activity in preschool children. *J Pediatr.* 2002; 140: 81–85. doi: [10.1067/mpd.2002.120693](#) PMID: [11815768](#)
33. Kajantie E, Strang-Karlsson S, Hovi P, Räikkönen K, Pesonen AK, Heinonen K et al. Adults born at very low birth weight exercise less than their peers born at term. *J Pediatr.* 2010; 157: 610–616. doi: [10.1016/j.jpeds.2010.04.002](#) PMID: [20493499](#)
34. Saigal S, Stoskopf B, Boyle M, Paneth N, Pinelli J, Streiner D et al. Comparison of current health, functional limitations, and health care use of young adults who were born with extremely low birth weight and normal birth weight. *Pediatrics.* 2007; 119: e562–e573. doi: [10.1542/peds.2006-2328](#) PMID: [17332176](#)
35. Odberg MD. Low birth weight young adults: quality of life, academic achievements and social functioning. *Acta Paediatr.* 2001; 100: 284–288. doi: [10.1111/j.1651-2227.2010.02096.x](#)

36. Yogev-Seligmann G, Hausdorff JM, Giladi N. The role of executive function and attention in gait. *Mov Disord*. 2008; 23: 329–342. doi: [10.1002/mds.21720](#) PMID: [18058946](#)
37. Anderson V. Executive function in children: Introduction. *Child Neuropsychol*. 2002; 8: 69–70. doi: [10.1076/chin.8.2.69.8725](#) PMID: [12638060](#)
38. Huang HJ, Mercer VS. Dual-task methodology: applications in studies of cognitive and motor performance in adults and children. *Pediatr Phys Ther*. 2001; 13: 133–140. 0898-5669/01/1303-0133 PMID: [17053670](#)
39. Beurskens R, Bock O. Age-related deficits of dual-task walking: a review. *Neural Plast*. 2012; 2012: 131608. doi: [10.1155/2012/131608](#) PMID: [22848845](#)
40. Al-Yahya E, Dawes H, Smith L, Dennis A, Howells D, Cockburn J. Cognitive motor interference while walking: a systematic review and meta-analysis. *Neurosci Biobehav Rev*. 2011; 35: 715–728. doi: [10.1016/j.neubiorev.2010.08.008](#) PMID: [20833198](#)
41. Sheridan PL, Solomont J, Kowall N, Hausdorff JM. Influence of executive function on locomotor function: divided attention increases gait variability in Alzheimer's disease. *J Am Geriatr Soc*. 2003; 51: 1633–1637. doi: [10.1046/j.1532-5415.2003.51516.x](#) PMID: [14687395](#)
42. Yogev G, Giladi N, Peretz C, Springer S, Simon ES, Hausdorff JM. Dual tasking, gait rhythmicity, and Parkinson's disease: which aspects of gait are attention demanding? *Eur J Neurosci*. 2005; 22: 1248–1256. doi: [10.1111/j.1460-9568.2005.04298.x](#) PMID: [16176368](#)
43. Hausdorff JM, Yogev G, Springer S, Simon ES, Giladi N. Walking is more like catching than tapping: gait in the elderly as a complex cognitive task. *Exp Brain Res*. 2005; 164: 541–548. doi: [10.1007/s00221-005-2280-3](#) PMID: [15864565](#)
44. Abbruzzese LD, Rao AK, Bellows R, Figueroa K, Levy J, Lim E, et al. Effects of manual task complexity on gait parameters in school-aged children and adults. *Gait Posture*. 2014; 40: 658–663. doi: [10.1016/j.gaitpost.2014.07.017](#) PMID: [25168911](#)
45. Cherrng RJ, Liang LY, Hwang IS, Chen JY. The effect of a concurrent task on walking performance of preschool children. *Gait Posture*. 2007; 26: 231–237. doi: [10.1016/j.gaitpost.2006.09.004](#) PMID: [17045803](#)
46. Huang HJ, Mercer VS, Thorpe DE. Effects of different concurrent cognitive tasks on temporal-distance gait variables in children. *Pediatr Phys Ther* 2003; 15: 105–113. doi: [10.1097/01.PEP.0000067886.96352.6B](#) PMID: [17057440](#)
47. Katz-Leurer M, Rotem H, Keren O, Meyer S. Effect of concurrent cognitive tasks on gait features among children post-severe traumatic brain injury and typically-developed controls. *Brain Injury*. 2011; 25: 581–586. doi: [10.3109/02699052.2011.572943](#) PMID: [21534735](#)
48. Yogev-Seligman G, Hausdorff JM, Giladi N. Do we always prioritize balance when walking? Towards an integrated model of task prioritization. *Mov Disord*. 2012; 27: 765–770. doi: [10.1002/mds.24963](#) PMID: [22419512](#)
49. Petermann F, Petermann U. (Eds.) Wechsler Intelligence Scale for Children (WISC-IV). Frankfurt, Germany: Pearson Assessment; 2011.
50. Petermann F. (Ed.) Movement Assessment Battery for Children. 2nd ed. Frankfurt, Germany: Pearson Assessment; 2008.
51. Grob A, Meyer CS, Hagmann-von Arx P. Intelligence and Development Scales. Bern, Switzerland: Hans Huber; 2009.
52. Hagmann-von Arx P, Grob A, Petermann F, Daseking M. Concurrent validity of the HAWIK-IV and the Intelligence and Development Scales (IDS). *Z Kinder Jugendpsychiatr Psychother*. 2012; 40: 41–50. PMID: [22161941](#)
53. Goodman R. The strengths and difficulties questionnaire: a research note. *J Child Psychol Psychiatry*. 1997; 38: 581e6. doi: [10.1111/j.1469-7610.1997.tb01545.x](#)
54. Thorpe DE, Dusing SC, Moore CG. Repeatability of temporospatial gait measures in children using the GAITRite electronic walkway. *Arch Phys Med Rehabil*. 2005; 86: 2342–2346. doi: [10.1016/j.apmr.2005.07.301](#) PMID: [16344033](#)
55. Rinehart NJ, Tonge BJ, Iannsek R, McGinley J, Brereton AV, Enticott PG, et al. Gait function in newly diagnosed children with autism: cerebellar and basal ganglia related motor disorder. *Dev Med Child Neurol*. 2007; 48: 819–820. doi: [10.1017/S0012162206001769](#)
56. Kressig RW, Beauchet O. European GAITRite Network Group. Guidelines for clinical applications of spatio-temporal gait analysis in older adults. *Aging Clin Exp Res*. 2006; 18: 174–176. doi: [10.1007/BF03327437](#) PMID: [16702791](#)
57. Hof AL. Scaling gait data to body size. *Gait Posture*. 1996; 4: 222–223.

58. Stansfield BW, Hillman SJ, Hazlewood ME, Lawson AM, Mann AM, Loudon IR, Robb JE. Normalisation of gait data in children. *Gait Posture*. 2003; 17: 81–87. PMID: 12535730
59. Dubost V, Kressig RW, Gonthier R, Herrmann FR, Aminian K, Najafi B, et al. Relationships between dual-task related changes in stride velocity and stride time variability in healthy older adults. *Hum Mov Sci*. 2006; 25: 372–382. doi: 10.1016/j.humov.2006.03.004 PMID: 16714067
60. Muhaidat J, Kerr A, Evans JJ, Skelton DA. Exploring gait-related dual-task tests in community-dwelling fallers and non-fallers: a pilot study. *Physiother Theory Pract*. 2013; 29: 351–370. doi: 10.3109/09593985.2012.752056 PMID: 23289962
61. Leitner Y, Barak R, Giladi N, Peretz C, Eshel R, Gruendlinger L, et al. Gait in attention deficit hyperactivity disorder: effects of methylphenidate and dual tasking. *J Neurol*. 2007; 254: 1330–1138. doi: 10.1007/s00415-006-0522-3 PMID: 17401735
62. Lindenberger U, Marsiske M, Baltes P. Memorizing while walking: increase in dual-task costs from young adulthood to old age. *Psychol Aging*. 2000; 15: 417–436. doi: 10.1037/0882-7974.15.3.417 PMID: 11014706
63. Bloem BR, Valkenburg VV, Slabbekoorn M, van Dijk JG. The multiple tasks test. Strategies in Parkinson's disease. *Exp Brain Res*. 2001; 137: 478–486. doi: 10.1007/s002210000672 PMID: 11355392
64. Cheng RJ, Liang LY, Chen YJ, Chen YJ. The effects of a motor and a cognitive concurrent task on walking in children with developmental coordination disorder. *Gait Posture*. 2009; 29: 204–207. doi: 10.1016/j.gaitpost.2008.08.003 PMID: 18809330
65. Ebersbach G, Dimitrijevic MR, Poewe W. Influence of concurrent tasks on gait: a dual-task approach. *Percept Mot Skills*. 1995; 81: 107–113. doi: 10.2466/pms.1995.81.1.107 PMID: 8532444
66. Yang YR, Chen YC, Lee CS, Cheng SJ, Wang RY. Dual-task-related gait changes in individuals with stroke. *Gait Posture*. 2007; 25: 185–190. doi: 10.1016/j.gaitpost.2006.03.007 PMID: 16650766
67. Erikson C, Allert C, Carlberg EB, Katz-Salomon M. Stability of longitudinal motor development in very low birthweight infants from 5 months to 5.5 years. *Acta Paediatr*. 2003; 92: 197–203. doi: 10.1111/j.1651-2227.2003.tb00526.x PMID: 12710646
68. Tombu M, Jolicoeur P. A central capacity sharing model of dual-task performance. *J Exp Psychol Hum Percept Perform*. 2003; 29: 3–18. doi: 10.1037/0096-1523.29.1.3 PMID: 12669744
69. Anderson PJ, De Luca CR, Hutchinson E, Spencer-Smith MM, Roberts G, Doyle LW, Victorian Infant Collaborative Study Group. Attention problems in a representative sample of extremely preterm/ extremely low birth weight children. *Dev Neuropsychol*. 2011; 36: 57–73. doi: 10.1080/87565641.2011.540538 PMID: 21253991
70. Pashler H. Dual-task interference in simple tasks: Data and theory. *Psychol Bull*. 1994; 116: 220–244. PMID: 7972591
71. Jaekel J, Baumann N, Wolke D. Effects of gestational age at birth on cognitive performance: A function of cognitive workload demands. *Plos One*. 2013; 8: e65219. doi: 10.1371/journal.pone.0065219 PMID: 23717694
72. Belmonti V, Berthoz A, Cioni G, Fiori S, Guzzetta A. Navigation strategies as revealed by error patterns on the Magic Carpet test in children with cerebral palsy. *Front Psychol*. 2015; 6: 880. doi: 10.3389/fpsyg.2015.00880 PMID: 26217250
73. Gozto Y, Vohr B, Lacadie C, Hampson M, Katz KH, Maller-Kesselman J, Schneider KC, Peterson BS, Rajeevan N, Makuch RW, Constable RT, Ment LR. Alterations in neural connectivity in preterm children at school age. *NeuroImage*. 2009; 48: 458–463. doi: 10.1016/j.neuroimage.2009.06.046 PMID: 19560547
74. Chester VL, Tingley M, Biden EN. A comparison of kinetic gait parameters for 3–13 year olds. *Clin Biomech*. 2006; 21: 726–732. doi: 10.1016/j.clinbiomech.2006.02.007
75. Ritter BC, Nelle M, Perrig W, Steinlin M, Everts R. Executive functions of children born very preterm—deficit or delay? *Eur J Pediatr*. 2013; 172: 473–483. doi: 10.1007/s00431-012-1906-2 PMID: 23247616
76. Spittle A, Orton J, Anderson P, Boyd R, Doyle LW. Early developmental intervention programmes post-hospital discharge to prevent motor and cognitive impairments in preterm infants. *Cochrane Database Syst Rev*. 2012; 12: CD005495. doi: 10.1002/14651858.CD005495.pub2 PMID: 23235624

APPENDIX C: Article 3

Manicolo, O. ⁺, Brotzmann, M. ⁺, Hagmann-von Arx, P., Grob, A., & Weber, P. Gait in children with autism spectrum disorder: Age-dependent decrease in gait variability and associations with motor skills. (⁺ shared first authorship). *Manuscript submitted for publication to Journal of Autism and Developmental Disorders*.

Draft February 15, 2016

Running head: Gait in children with ASD

Gait in children with autism spectrum disorder: Age-dependent decrease in gait variability and associations with motor skills

Olivia Manicolo^{1,+,*}, Mark Brotzmann^{2,+}, Priska Hagmann-von Arx¹, Alexander Grob¹, Peter Weber²

¹Department of Psychology, University of Basel, Basel, Switzerland

²Division of Neuropediatrics and Developmental Medicine, University Children's Hospital
Basel, Basel, Switzerland

+ Shared first authorship

* Corresponding author: Olivia Manicolo, Department of Psychology, University of Basel,
Missionsstrasse 62, 4055 Basel, Switzerland; Tel. +41 61 267 06 30; fax +41 61 267 06 61; e-mail:
olivia.manicolo@unibas.ch

Conflict of interest: The authors declare that they have no conflict of interest.

Abstract

Gait and its associations with prewalking motor milestones, motor skills, and age were investigated in 32 children with autism spectrum disorder (ASD) and 36 typically developing controls. Gait was assessed using GAITRite recordings of spatiotemporal and variability gait parameters. Parents reported their child's prewalking motor milestones. Motor skills were assessed using the Movement Assessment Battery for Children. Children with ASD showed higher gait variability than controls, indicating a less regular walking pattern. In children with ASD gait variability was negatively associated with motor skills, but there was no such association with prewalking motor milestones. The higher gait variability in children with ASD showed an age-dependent decrease, suggesting that their gait regularity converges toward that of typically developing children.

Keywords: Gait variability, ASD, children, motor milestones, motor skills, gait maturation

Gait in children with autism spectrum disorder: Age-dependent decrease in gait variability and associations with motor skills

Autism spectrum disorder (ASD) is an inclusive term for a group of biologically based neurodevelopmental disorders characterized by the core symptoms of impairments of social communication and repetitive behaviors with limited interests (American Psychiatric Association, 2013). Furthermore, it has been suggested that motor dysfunction may also be a core symptom of ASD and may predate social and communicative impairments (Teitelbaum et al., 2004; Teitelbaum, Teitelbaum, Nye, Fryman, & Maurer, 1998).

Motor symptoms of children with ASD involve delays in motor milestone development, with findings indicating that children with ASD acquire abilities such as sitting and walking autonomously several months later than typically developing children (e.g., Provost, Lopez, & Heimerl, 2007; Segawa & Nomura, 1991), who reach these motor milestones approximately at the age of 6 and 12 months, respectively (Størvold, Aarethun, & Bratberg, 2013). Further, children with ASD show impairments in motor skills, including difficulties with gross and fine motor function and coordination (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Ghaziuddin, Tsai, & Ghaziuddin, 1992; Green et al., 2009; Hilton, Zhang, Whilte, Klohr, & Constantino, 2012; Jansiewicz et al., 2006; Kopp, Beckung, & Gillberg, 2010; Liu & Breslin, 2013; Paquet, Olliac, Golse, & Vaivre-Douret, 2015). Impaired motor development in individuals with ASD can compromise the ability to perform activities of daily living. For example, when children with ASD show problems in fine motor control this may affect tasks such as tying shoes or writing, as well as social play such as riding a bike, throwing a ball, and participating in team sports (Liu & Breslin, 2013).

Further, gross motor impairments can lead to clumsy movement patterns—including walking, which is the most important mode of human locomotion (Adolph, Vereijken, &

Shrout, 2003; Kindregan, Gallagher, & Gormeley, 2015). In this vein, Shetreat-Klein, Shinnar, and Rapin (2012) reported the qualitative finding that during walking, children with ASD lack consistency, smoothness, and coordination compared to controls. Furthermore, it has been observed that children with ASD are more prone to idiopathic toe walking than typically developing children (Accardo & Barrow, 2015; Barrow, Jaworski, & Accardo, 2011; Marcus, Sinnott, Bradley, & Grey, 2010).

However, so far, only a small number of empirical studies have investigated walking patterns of children with ASD using quantitative methods, such as electronic walkway systems or electronic footswitches. Early research showed alterations in spatiotemporal gait measures such as reduced stride length and increased stride time for children with ASD compared to typically developing children (Ambrosia, Courchesne, & Kaufman, 1998; Vilensky, Damasio, & Maurer, 1981). However, subsequent studies have found mixed results, with some reporting significantly shorter stride length and increased stride time for children with ASD compared to controls, as in the earlier studies (e.g., Lim, O'Sullivan, Choi, & Kim, 2016; Vernazza-Martin et al., 2005; Weiss, Moran, Parker, & Foley, 2013) but others reporting no significant group differences for these gait measures (e.g., Chester & Calhoun, 2012; Rinehart, Tonge, Bradshaw, et al., 2006). Overall, the inconsistency in results may be due to differences in methodology (i.e., different gait analysis systems) and inclusion criteria (e.g., gender, age, intellectual functioning).

In contrast to the inconsistency in findings on spatiotemporal gait parameters, a more homogeneous picture emerges for measures of gait variability (i.e., stride-to-stride fluctuations), representing the regularity and automaticity of gait (cf. Hausdorff, 2005). Studies assessing gait variability have consistently reported higher gait variability among children with ASD compared to typically developing children (Nayate et al., 2012; Rinehart, Tonge, Bradshaw, et al., 2006; Rinehart, Tonge, Iansek, et al., 2006). For example, Nayate et

al. (2012) investigated 11 children (average age: 12.8 years) diagnosed with ASD, who showed significantly increased variability for stride length as well as increased step width compared to controls. This is in line with the findings reported by Rinehart, Tonge, Bradshaw, et al. (2006) of increased stride length variability in a sample of 10 children with ASD (average age: 10.7 years) compared to typically developing controls but no between-group differences for spatiotemporal measures such as velocity and stride length. The same holds true for the findings reported by Rinehart, Tonge, Iansek, et al. (2006) of no between-group differences for spatiotemporal measures (e.g., velocity, stride length), whereas stride length variability and stride time variability were significantly increased in their sample of 11 children with ASD (average age: 5.8 years) compared to controls. These findings may lend further support to the notion that measures of gait variability provide a more discriminant and sensitive measure of gait performance than spatiotemporal gait variables (Hausdorff, 2005; Lord, Howe, Greenland, Simpson, & Rochester, 2011)

In terms of gait development, previous results on walking performance of typically developing children have shown that spatiotemporal and variability measures of gait seem to undergo temporally distinct developmental trajectories. With increasing age, children show improvements in spatiotemporal gait measures, including enhanced velocity and step length, and reach a mature gait pattern at about 7 years (Adolph et al., 2003; Hillman, Stansfield, Richardson, & Robb, 2009; Holm, Tveter, Frederiksen, & Vollestad, 2009). Gait variability, on the other hand, further develops beyond this age with gait becoming more regular during middle and late childhood before reaching maturity in adolescence (Froehle, Nahhas, Sherwood, & Duren, 2013; Hausdorff, Zeman, Peng & Goldberger, 1999; Hillman et al., 2009; Lythgo, Wilson, & Galea, 2009, 2011). These results highlight the importance of including variability measures in addition to spatiotemporal measures in gait analysis.

Although a small percentage of children with ASD lose their symptoms that support a diagnosis of ASD at some point during their life (Fein et al., 2013), findings on outcomes during adolescence and adulthood suggest that in most cases ASD is a lifelong condition that involves persistent and stable impairments in mental, linguistic, social, and motor abilities (Eaves & Ho, 2008; Nordin & Gillberg, 1998; Van Damme, Simons, Sabbe & van West, 2015). So far, it has not been investigated whether this also holds true for gait impairments of children with ASD. Nonetheless, studies of children with other neurodevelopmental disorders such as attention-deficit/hyperactivity disorder (ADHD) have indicated that their initially higher gait variability shows an age-dependent decrease, with gait performance becoming more regular and converging toward typically developing controls during childhood (Manicolo, Grob, Lemola, & Hagmann-von Arx, 2016). However, for subjects with ASD it remains unclear whether this developmental pattern also emerges or whether the previously reported alterations of gait variability (Nayate et al., 2012; Rinehart, Tonge, Bradshaw, et al., 2006; Rinehart, Tonge, Iansek, et al., 2006) remain persistent and therefore nonconvergent toward controls during childhood.

In sum, several studies reported impaired motor development in children with ASD, including delayed acquisition of early motor milestones (e.g., sitting and walking autonomously; e.g., Provost et al., 2007; Segawa & Nomura, 1991), impaired motor function involving fine and gross motor skills (e.g., Liu & Breslin, 2013), and alterations in spatiotemporal and variability gait characteristics. However, there are important gaps in the research: Although signs of impaired motor development possibly affecting later gait development may be present as early as infancy in subjects with ASD (Teitelbaum et al., 1998), no study has so far investigated whether prewalking motor milestones such as sitting and walking autonomously are associated with later gait development. Furthermore, whereas recent studies indicated impairments of motor skills (e.g., Paquet et al., 2015) and higher gait

7

variability (e.g., Nayate et al., 2012) in children with ASD, no study has investigated possible associations between motor skills and gait variability. Additionally, it remains unclear whether in children with ASD gait variability measures show age-dependent alterations during childhood. The aim of the present study was therefore to further examine gait performance and to collect information on prewalking motor milestones as well as to assess motor skills of children with ASD by including a larger sample with a wider age range than used in previous studies. We hypothesized that children with ASD would show a less stable and less regular walking pattern than controls. Additionally, we hypothesized that children with ASD would show a delayed acquisition of motor milestones and impairments in motor skills. Finally, to address what has been lacking in research, we explored whether measures of gait variability are associated with motor milestones and motor skills. Further we studied whether — with increasing age — gait variability measures of children with ASD decrease or remain persistent and nonconvergent toward that of typically developing children.

Methods

Participants

Our sample of children with ASD was derived from an initial cohort of 98 patients who were diagnosed with ASD according to the ICD-10 (World Health Organization, 1992) and were treated between 2008 and 2013 at the University Children's Hospital Basel (Switzerland). Given that previous studies indicated differences between children with Asperger's syndrome (AS) and children with infantile or atypical autism in their neurological basis, clinical characteristics, and comorbidities (Remscheid & Kamp-Becker, 2007) as well as differences in motor performance (Papadopoulos et al., 2012) including gait patterns (e.g., Rinehart, Tonge, Bradshaw, et al., 2006), we excluded children with AS or pervasive developmental disorder not otherwise specified (PDD-NOS) from the present study. Furthermore, children with comorbid cerebral palsy or otherwise-classified motor handicap

were excluded from the recruitment process. Of the remaining 52 children, 6 children could not be traced, and of the 46 parents who were contacted by phone, 38 agreed to allow their children to participate. For 2 children data collection was not possible because they did not understand the test instructions or were noncompliant. Four children with ASD showed idiopathic toe walking resulting in erroneous gait data and consequently had to be excluded from data analysis.

The final ASD sample for this study consisted of 32 children aged between 4.1 and 16.9 years (mean age = 9.2 years; 27 boys, 5 girls) including 29 children diagnosed with infantile autism and three children with atypical autism. A genetic examination was performed in 10 of the 32 children diagnosed with ASD with karyotype, exclusion of fragile X syndrome, or exclusion of other microdeletion syndromes using microarray-based comparative genomic hybridization. For two of those children a genetic disorder was confirmed (Klinefelter syndrome, deletion Xp22.11).

For the control group, typically developing siblings of participating children with ASD as well as children from private surroundings of coworkers were recruited. The control group consisted of 36 children aged between 4.1 and 16.5 years (mean age = 9.0 years, 31 boys, 5 girls). Table 1 summarizes group characteristics as well as medication status of children with ASD. As shown in Table 1, the two groups of children were similar with respect to age, sex, height, weight, and leg length.

please insert Table 1 about here

Materials

Gait Assessment

Gait was measured using the GAITRite electronic walkway system (GAITRite

Platinum; CIR Systems, USA). This system consists of a 701-cm-long walkway with 23,040 integrated pressure sensors. A 1.25-m nonrecordable zone was added on each end of the walkway to minimize the effects of acceleration and deceleration. Therefore, children walked approximately 10 m per walk and each walk comprised on average eight steps. The validity and reliability of gait assessment using GAITRite for children is well established (Thorpe, Dusing, & Moore, 2005). All gait analyses were performed according to the European guidelines for spatiotemporal gait analysis (Kressig, Beauchet, & European GAITRite Network Group, 2006). The following seven spatiotemporal and variability measures of gait were evaluated: velocity (obtained by dividing the distance traveled by ambulation time expressed in centimeters per second); stride time (the time elapsed between the first contact of two consecutive footfalls of the same foot expressed in seconds); stride length (the distance between the heel points of two consecutive footfalls of the same foot expressed in centimeters); base of support (the perpendicular distance from heel point of one footfall to the line of progression of the opposite foot expressed in centimeters); gait variability, assessed as variability in stride velocity, stride time, and stride length using the percentage coefficient of variation ($CV = \text{standard deviation}/\text{mean} \times 100$). While velocity as a general indicator of functional performance is the most common reported gait outcome (Al-Yahya et al., 2011), stride length and stride time reflect gait patterning (Gabell & Nayak, 1984), and base of support measures equilibrium (Nayate et al., 2012). Gait variability, on the other hand, reflects the regularity of gait and forms a more discriminant and sensitive measure of subtle changes in gait performance (Hausdorff, 2005). Height, weight, and leg length were measured prior to gait assessment. Then, children were given one demonstration trial and a practice trial before performing 10 trials of walking. Children were instructed to walk at their normal pace. After each walk, data were analyzed using GAITRite software. Gait parameters were averaged over the trials for further data analysis.

Motor Milestones and Motor Skills Assessment

Information about motor milestones was gathered by asking the parents to report at what age (in months) their child was able to sit upright autonomously and walk autonomously. Motor skills were assessed using the German version of the Movement Assessment Battery for Children, 2nd edition (M-ABC-2; Petermann, 2008), which is an individually administered standardized measure of motor function for children from 3 to 16 years of age with established reliability and validity (Wagner et al., 2011). There are three age-related item sets, each consisting of eight tasks measuring manual dexterity (three tasks), ball skills (two tasks), and balance (three tasks). Item scores can be combined to form an overall score with a normative mean of 10 and standard deviation of 3.

Statistical Analysis

Data were analyzed using IBM SPSS Statistics (Version 20). To test for group differences in demographic characteristics, a χ^2 test for categorical variables or an independent samples t test for continuous variables was used. Group differences in spatiotemporal and variability measures of gait, as well as motor milestones and motor skills, were assessed using multivariate analysis of variance (MANOVA). The F statistic, p value (two tailed), and effect sizes (η^2) are reported. If an extreme value (defined as a score exceeding 3 SD s from the group mean) occurred in the gait measures, scores were truncated to $\pm 3 SD$.

Further, we assessed whether gait variability was associated with motor milestones and motor skills, and if so, whether these associations differed between children with ASD and controls. As we were interested in a general marker of motor skills, the M-ABC-2 overall score was included in the following analyses. To analyze whether associations of gait variability with motor milestones and motor skills differed in children with ASD and controls (i.e., whether group [ASD vs. control] acted as a moderator of these associations), three

hierarchical regression analyses were conducted following the procedure proposed by Aiken, West, and Reno (1991). In each hierarchical regression the control variable leg length was entered in the first block. Then, group (ASD vs. control) and the respective predictor (i.e., sit upright autonomously, walk autonomously, or M-ABC-2 overall score) were entered in the next block. Finally, the interaction term between group (ASD vs. control) and the corresponding predictor was entered in the last block.

Additionally, a hierarchical regression was conducted to examine whether the association between gait variability measures and age differed in children with ASD and controls (i.e., whether group [ASD vs. control] acted as a moderator of the association). The control variable leg length was entered in the first block. Group (ASD vs. control) and age were entered in the next block and in the last block the interaction term Group (ASD vs. control) \times Age was entered.

If a significant interaction was found (indicating a significant moderation effect), then the interaction was graphed by computing the predicted gait variability measures separately for children with ASD and controls. Single slope analyses were used to evaluate whether the slopes in the graphs were significantly different from zero (Aiken et al., 1991).

Results

Gait Measures, Motor Milestones, and Motor Skills of Children with ASD and Controls

The results of the gait measures, motor milestones, and motor skills are presented in Table 2. For gait measures, the MANOVA revealed a significant effect of group (Wilks's multivariate test), $F(7,60) = 8.709, p < .001, \eta^2 = .504$, with univariate tests showing significant higher values for children with ASD on all measures of gait variability: CV stride velocity ($p = .001, \eta^2 = .167$); CV stride time ($p < .001, \eta^2 = .207$); and CV stride length ($p < .001, \eta^2 = .174$), as well as base of support ($p < .001, \eta^2 = .196$), whereas no group differences emerged for the other spatiotemporal gait measures velocity, stride time, and stride length.

12

For motor milestones the MANOVA revealed a significant effect of group (Wilks's multivariate test), $F(2,53) = 4.406, p = .017, \eta^2 = .143$, with univariate tests showing that children with ASD were able to sit upright autonomously at a similar age as controls at approximately 7 to 8 months, but that controls were able to walk autonomously at about 13.3 months and thus at an earlier age than children with ASD who walked at about 16.4 months ($p = .012, \eta^2 = .111$).

Furthermore, for motor skills assessed with the M-ABC-2, the MANOVA revealed a significant effect of group (Wilks' multivariate test), $F(4,50) = 21.991, p < .001, \eta^2 = .638$, with univariate tests showing significant lower scores of children with ASD on all three subscales of the M-ABC-2—manual dexterity ($p < .001, \eta^2 = .419$); ball skills ($p < .001, \eta^2 = .363$); and balance ($p < .001, \eta^2 = .487$) — as well as for the M-ABC-2 overall score ($p < .001, \eta^2 = .597$; Table 2).

please insert Table 2 about here

Associations of Gait Variability Measures With Motor Milestones and Motor Skills

Controlled for leg length, motor milestones (i.e., sit upright autonomously, walk autonomously) showed no significant associations with gait variability in a hierarchical regression analysis, whereas a higher M-ABC-2 overall score was significantly associated with lower scores on all gait variability measures: CV stride velocity ($\beta = -.423, p = .016$), CV stride time ($\beta = -.350, p = .045$), CV stride length ($\beta = -.375, p = .027$).

Next moderated hierarchical regression analyses were calculated with interaction terms between group (ASD vs. control) and the predictors (i.e., sit upright autonomously, walk autonomously, M-ABC-2 overall score), controlling for leg length and the corresponding predictor. These analyses revealed three significant interaction terms (Table

13

3): Group (ASD vs. control) moderated the association between M-ABC-2 overall score and CV stride velocity ($\beta = .310, p = .015$), CV stride time ($\beta = .315, p = .014$), and CV stride length ($\beta = .254, p = .042$).

please insert Table 3 about here

As depicted in Figure 1, in children with ASD, the M-ABC-2 overall score was significantly associated with all measures of gait variability: CV stride velocity ($\beta = -.591, p = .010$), CV stride time ($\beta = -.567, p = .013$), and CV stride length ($\beta = -.531, p = .018$), such that higher M-ABC-2 overall scores were related to lower gait variability. In controls there were no significant associations between their M-ABC-2 overall score and gait variability measures.

please insert Figure 1 about here

Associations of Gait Variability Measures With Age

Controlling for leg length, hierarchical regression analyses for the combined sample showed that age was significantly associated with lower scores on all gait variability measures: CV stride velocity ($\beta = -.529, p = .004$), CV stride time ($\beta = -.566, p = .002$), CV stride length ($\beta = -.541, p = .002$). Further, moderated hierarchical regression analyses were calculated with group (ASD vs. control) \times Age interaction terms, controlling for leg length and age. These analyses revealed three significant interaction terms (Table 3). Group (ASD vs. control) moderated the association between age and CV stride velocity ($\beta = .197, p = .034$), CV stride time ($\beta = .269, p = .002$), and CV stride length ($\beta = .207, p = .017$).

As depicted in Figure 2, in children with ASD, age was significantly associated with

14

all measures of gait variability: CV stride velocity ($\beta = -.802, p = .004$), CV stride time ($\beta = -.818, p = .003$), CV stride length ($\beta = -.800, p = .002$), such that higher age was related to lower gait variability, whereas in controls there were no associations between age and gait variability measures.

please insert Figure 2 about here

Discussion

Our goal in the present study was to investigate gait and its associations with prewalking motor milestones as well as with motor skills in children with ASD. Moreover, we aimed to examine age-dependent alterations of gait performance and tested whether with increasing age, gait variability of children with ASD decreases and converges toward that of typically developing children.

In line with previous studies (Nayate et al., 2012; Rinehart, Tonge, Bradshaw, et al., 2006; Rinehart, Tonge, Iansek, et al., 2006), we found that children with ASD walked with significantly higher gait variability (i.e., higher variability for stride velocity, stride time, and stride length) and a significantly wider base of support than controls. These findings lend support to the notion of a less regular and less steady walking pattern in children with ASD (Nobile et al., 2010; Shetreat-Klein et al., 2014). Furthermore, in line with Rinehart, Tonge, Bradshaw, et al. (2006) and Rinehart, Tonge, Iansek, et al. (2006), we found no group differences for velocity, stride time, or stride length such that children with ASD did not show any significant alterations in these gait parameters compared to controls. Hence, our finding that children with ASD show similar performance in spatiotemporal gait measures compared to typically developing children but appear to show difficulties with the regularity of gait cycles (i.e., higher gait variability) highlights the importance of including variability

measures, as they may provide a more discriminant and sensitive measure of gait performance than other gait parameters (Hausdorff, 2005; Lord et al., 2011).

Our results showed that the two groups of children were able to sit upright autonomously at a similar age, between the 7th and 8th month of life. On the other hand, children from the control group were able to walk autonomously at an earlier age (i.e., mean age 13.3 months) than children with ASD (i.e., mean age 16.4 months). This is in line with previous studies reporting that age at initial walking autonomously is delayed in children with ASD (Ozonoff et al., 2008; Provost et al., 2007; Segawa & Nomura, 1991; Teitelbaum et al., 1998) whereas only marginal differences were reported for the age at first sitting autonomously (Ozonoff et al., 2008). When examining gross motor development, including sitting and walking autonomously, of infants later diagnosed with ASD, Ozonoff et al. (2008) reported a slower rate of development for walking compared to typically developing controls. However, our results indicate that those early motor milestones are not associated with development of gait regularity of children with ASD later in childhood, since we found no significant association of the age of sitting and walking autonomously with any measures of later gait variability. Therefore, our findings provide preliminary evidence to refute the assumption that the age of reaching the motor milestones of sitting and walking autonomously during infancy will predict later gait development during childhood and into adolescence among subjects with ASD. However, it is notable that the information on early motor milestones is based on retrospective parental reports in our study and hence needs to be interpreted with caution.

In line with previous research (e.g., Green et al., 2002, 2009; Hilton et al., 2007; Liu & Breslin, 2013), our findings additionally show that children with ASD had significant difficulties with motor skills, represented by a lower M-ABC-2 overall score compared to controls and significant impairments in each of the areas examined by this test: manual

dexterity, ball skills, and balance. Furthermore, our results are the first to show that motor skills assessed by the M-ABC-2 overall score are associated with gait regularity in children with ASD, such that better motor skills go along with a more regular walking pattern (i.e., lower gait variability measures), whereas no such association was found for controls. Hence, gait regularity can be assumed to be a further dimension of motor dysfunction associated with ASD (Paquet et al., 2015) and may be part of a more general impairment in movement that ranges from fine and gross motor skills measured by the M-ABC-2 to the planning and execution of skilled motor sequences such as walking (Minshew, Sung, Jones & Furman, 2004).

Further, we found that age was associated with all gait variability measures such that with increasing age, variability in stride velocity, stride length, and stride time decreased. These results support the notion that gait continues to develop across childhood and becomes more regular toward adolescence (Froehle et al., 2013; Hausdorff et al., 1999; Hillman et al., 2009; Lythgo et al., 2009, 2011). Additionally, we found that children with ASD displayed an age-dependent decrease of their gait variability toward that of controls. A similar developmental pattern has recently been reported in a sample of children with ADHD aged 8–13 years (off or without medication) with gait performance becoming more regular with increasing age and converging toward that of typically developing controls (Manicolo et al., 2016). Although ASD and ADHD are each distinguished by a separate set of core symptoms in the *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; American Psychiatric Association, 2013), increasing research highlights common behavioral, cognitive, and neural features (Dougherty, Evans, Myers, Moore, & Michael, 2015). One of the shared neural features is a delay in brain maturation in prefrontal structures (Shaw et al., 2007, 2012; Zilbovicius et al., 1995), which, among other things, include higher order motor control regions (Shaw et al., 2007, 2012). Since we found an age-dependent decrease in gait

variability in children with ASD and a recent study found a similar developmental pattern in children with ADHD (Manicolo et al., 2016), one could hypothesize that this common maturational process in gait regularity may be associated with a delayed maturation of frontal brain regions found for both ASD and ADHD (Shaw et al., 2007, 2012; Zilbovicius et al., 1995). However, another brain region that consistently exhibits abnormalities such as volume reduction in both ASD and ADHD is the cerebellum (Dougherty et al., 2015), which is importantly involved in motor movement and locomotor activity (e.g., Anderson, Polcari, Lowen, Renshaw, & Teicher, 20014; Pasini, D'Agati, Pitzianti, Casarelli, & Curatolo, 2012). Future research might further investigate possible associations between brain maturation, structural abnormalities, and gait patterns to better understand the neural underpinning of the here reported alterations and age-dependent decrease in gait regularity among subjects with ASD.

Our study has strengths and limitations. We consider it a strength that gait characteristics were assessed using the objective electronic GAITRite system with proven reliability as well as validity (Thorpe et al., 2005) and allowing children to wear their normal clothes and shoes during gait assessment. We additionally included a standardized evaluation tool by using the M-ABC-2 to assess motor skills of children with ASD and controls. This is in accordance with Rinehart, Tonge, Iansek, et al. (2006), who suggested that due to the clinical heterogeneity of ASD, assessments of motor functioning using standardized measures should be included when investigating gait data. A further strength of our study is the investigation of a homogenous cohort by including only children with infantile and atypical autism and excluding children with AS or PDD-NOS. Hence, our findings cannot be generalized to children with AS or PDD-NOS. Furthermore, we examined a larger sample than in previous studies on gait in children with ASD and covered a wide age range by including subjects from 4 to 17 years. However, our analyses were performed on cross-

sectional data, whereas the investigation of maturational patterns related to gait developmental and the objective assessment of infant prewalking milestones would require future studies following a longitudinal research approach. Furthermore, we analyzed spatiotemporal gait parameters, as the walkway system GAITRite allows neither the investigation of peculiar walking patterns such as toe walking, which has previously been reported for children with ASD (Accardo & Barrow, 2015; Barrow et al., 2011; Marcus et al., 2010), nor the qualitative analysis of gait motion, such as head and trunk posturing (Rinehart, Tonge, Bradshaw, et al., 2006). Hence, future studies might investigate whether qualitative aspects of gait motion also show associations with motor skills and whether they follow a similar age-dependent improvement to what we found for spatiotemporal measures of gait variability. Finally, due to the small number of children with ASD being medicated in our sample, we could not investigate possible medication effects. This as well as whether similar findings to those obtained in our study would result for drug-naïve subjects with ASD should be addressed in future studies.

In sum, this study provides support for a less regular and less stable walking pattern of children with ASD. Additionally, our findings are the first to indicate that among subjects with ASD, gait variability is associated with motor skills, whereas infant prewalking motor milestones seem not to be associated with later gait development during childhood. Furthermore, our results are the first to lend support to the notion of an age-dependent decrease in gait variability in children with ASD and hence an increase in gait regularity toward adolescence. Since differences in motor development are not included as primary diagnostic categories for ASD (American Psychiatric Association, 2013), the findings of this study support the importance of considering motor functioning, including gait parameters, in addition to other developmental skill areas outlined in diagnostic manuals. Such a shift in focus to a movement perspective may provide new insights on ASD, possibly helping with

determining the degree of specificity of deficits and the development of useful tools for diagnosis (Kindregan et al., 2015; Leary & Hill, 1996; Provost et al., 2007).

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

References

- Accardo, P. J., & Barrow, W. (2015). Toe walking in autism: further observations. *Journal of Child Neurology*, 30, 606-609.
- Adolph, K. E., Vereijken, B., & Shrout, P. E. (2003). What changes in infant walking and why. *Child Development*, 74, 475-497.
- Aiken, L. S., West, S. G., & Reno, R. R. (1991). *Multiple regression: Testing and interpreting interactions*. London, England: Sage.
- Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, D., & Cockburn, J. (2011). Cognitive motor interference while walking: A systematic review and meta-analysis. *Neuroscience & Biobehavioral Reviews*, 35, 715-728.
- Ambrosia, D., Courchesne, E., & Kaufman, K. (1998). Motion analysis of patients with infantile Autism. *Gait and Posture*, 7, 188.
- American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.
- Anderson, C. M., Polcari, A., Lowen, S. B., Renshaw, P. F., & Teicher, M. H. (2014). Effects of methylphenidate on functional magnetic resonance relaxometry of the cerebellar vermis in boys with ADHD. *American Journal of Psychiatry*, 159, 1322-1328.
- Barrow, W., Jaworski, M., & Accardo, P. J. (2011). Persistent toe walking in autism. *Journal of Child Neurology*, 26, 619-621.
- Chester, V. L., & Calhoun, M. (2012). Gait symmetry in children with autism. *Autism Research and Treatment*, 2012.
- Dougherty, C. C., Evans, D. W., Myers, S. M., Moore, G. J., & Michael, A. M. (2015). A comparison of structural brain imaging findings in autism spectrum disorder and attention-deficit hyperactivity disorder. *Neuropsychology Review*. Advance online publication.

- Eaves, L. C., & Ho, H. H. (2008). Young adult outcome of autism spectrum disorders. *Journal of Autism and Developmental Disorders*, 38, 739-747.
- Fein, D., Barton, M., Eigsti, I. M., Kelley, E., Naigles, L., Schultz, R. T., ... Troyb, E. (2013). Optimal outcome in individuals with a history of autism. *Journal of Child Psychology and Psychiatry*, 54, 195-205.
- Froehle, A. W., Nahhas, R. W., Sherwood, R. J., & Duren, D. L. (2013). Age-related changes in spatiotemporal characteristics of gait accompany ongoing lower limb linear growth in late childhood and early adolescence. *Gait and Posture*, 38, 14-19.
- Fournier, K. A., Hass C. J., Naik, S. K., Lodha, N., & Cauraugh, J. H. (2010). Motor coordination in autism spectrum disorders: A synthesis and meta-analysis. *Journal of Autism and Developmental Disorder*, 40, 1227-1240.
- Gabell, A., & Nayak, U. S. (1984). The effect of age on variability in gait. *Journal of Gerontology*, 39, 662-666.
- Ghaziuddin, M., Tsai, L. Y., & Ghaziuddin, N. (1992). Brief report: A reappraisal of clumsiness as a diagnostic feature of Asperger syndrome. *Journal of Autism and Developmental Disorders*, 22, 651-656.
- Green, D., Baird, G., Barnett, A. L., Henderson, L., Huber, J., & Henderson, S. E. (2002). The severity and nature of motor impairment in Asperger's syndrome: A comparison with specific developmental disorder of motor function. *Journal of Child Psychology and Psychiatry*, 43, 655-668.
- Green D., Charman T., Pickles, A., Chandler, S., Loucas, T., Simonoff, E., & Baird, G. (2009). Impairment in movement skills of children with autistic spectrum disorders. *Developmental Medicine and Child Neurology*, 51, 311-316.
- Hausdorff, J. M. (2005). Gait variability: Methods, modeling and meaning. *Journal of Neuroengineering and Rehabilitation*, 2.

- Hausdorff, J. M., Zemani, L., Peng, C.-K., & Goldberger, A. L. (1999). Maturation of gait dynamics: Stride-to-stride variability and its temporal organization in children. *Journal of Applied Physiology*, 86, 1040-1047.
- Hillman, S. J., Stansfield, B. W., Richardson, A. M., & Robb, J. E. (2009). Development of temporal and distance parameters of gait in normal children. *Gait and Posture*, 29, 81-85.
- Hilton, C., Wente, L., LaVesser, P., Ito, M., Reed, C., & Herzberg, G. (2007). Relationship between motor skill impairment and severity in children with Asperger syndrome. *Research in Autism Spectrum Disorders*, 1, 339-349.
- Hilton, C. L., Zhang, Y., Whilte, M. R., Klohr, C. L., & Constantino, J. (2012). Motor impairment in sibling pairs concordant and discordant for autism spectrum disorders. *Autism*, 16, 430-441.
- Holm, I., Tveter, A. T., Frederiksen, P. M., & Vollestad, N. (2009). A normative sample of gait and hopping on one leg parameters in children 7-12 years of age. *Gait and Posture*, 27, 91-96.
- Jansiewicz, E. M., Goldberg, M. C., Newschaffer C. J., Denckla, M. B., Landa, R., & Mostofsky, S. H. (2006). Motor signs distinguish children with high functioning autism and Asperger's syndrome from controls. *Journal of Autism and Developmental Disorders*, 36, 613-621.
- Kindregan, D., Gallagher, L., & Gormley, J. (2015). Gait deviations in children with autism spectrum disorders: A review. *Autism Research and Treatment*, 2015.
- Kopp, S., Beckung, E., & Gillberg, C. (2010). Developmental coordination disorder and other motor control problems in girls with autism spectrum disorder and/or attention-deficit/hyperactivity disorder. *Research in Developmental Disabilities*, 31, 350-361.

- Kressig, R. W., Beauchet, O., & European GAITRite Network Group. (2006). Guidelines for clinical applications of spatio-temporal gait analysis in older adults. *Aging Clinical and Experimental Research*, 18, 174-176.
- Leary, M. R., & Hill, D. A. (1996). Moving on: Autism and movement disturbance. *Mental Retardation*, 34, 39-53.
- Lim, B. O., O'Sullivan, D., Choi, B. G., & Kim, M. Y. (2016). Comparative gait analysis between children with autism and age-matched controls: analysis with temporal-spatial and foot pressure variables. *Journal of Physical Therapy Science*, 28, 286-292.
- Liu, T., & Breslin, C. M. (2013). Fine and gross motor performance of the MABC-2 by children with autism spectrum disorder and typically developing children. *Research in Autism Spectrum Disorders*, 7, 1244-1249.
- Lord, S., Howe, T., Greenland, J., Simpson, L., & Rochester, L. (2011). Gait variability in older adults: A structured review of testing protocol and clinimetric properties. *Gait and Posture*, 34, 443-450.
- Lythgo, N., Wilson, C., & Galea, M. (2009). Basic gait and symmetry measures for primary school-aged children and young adults whilst walking barefoot and with shoes. *Gait and Posture*, 30, 502-506.
- Lythgo, N., Wilson, C., & Galea, M. (2011). Basic gait and symmetry measures for primary school-aged children and young adults II. Walking at slow, free and fast speed. *Gait and Posture*, 33, 29-35.
- Manicolo, O., Grob, A., Lemola, S., & Hagmann-von Arx, P. (2016). Age-related decline of gait variability in children with attention-deficit/hyperactivity disorder: Support for the maturational delay hypothesis in gait. *Gait and Posture*, 44, 245-249.

- Marcus, A., Sinnott, B., Bradley S., & Grey, I. (2010). Treatment of idiopathic toe-walking in children with autism using GaitSpot Auditory Speakers and simplified habit reversal. *Research in Autism Spectrum Disorders*, 4, 260-267.
- Minshew, N. J., Sung, K., Jones, B. L., & Furman, J. M. (2004). Underdevelopment of the postural control system in autism. *Neurology*, 63, 2056-2061.
- Nayate, A., Tongue, B. J., Bradshaw, J. L., McGinley, J. L., Iansek, R., & Rinehart, N. J. (2012). Differentiation of high-functioning autism and Asperger's disorder based on neuromotor behaviour. *Journal of Autism and Developmental Disorders*, 42, 707-717.
- Nobile, M., Perego, P., Piccinini, L., Mani, E., Rossi, A., Bellina, M., & Molteni, M. (2010). Further evidence of complex motor dysfunction in drug naive children with autism using automatic motion analysis of gait. *Autism*, 15, 263-283.
- Nordin, V., & Gillberg, C. (1998). The long-term course of autistic disorders: Update on follow-up studies. *Acta Psychiatrica Scandinavica*, 97, 99-108.
- Ozonoff, S., Young, G. S., Goldring, S., Greiss-Hess, L., Herrera, A. M., Steele, J., Macari, S., Hepburn, S., & Rogers, S. J. (2008). Gross motor development, movement abnormalities, and early identification of autism. *Journal of Autism and Developmental Disorders*, 38, 644-656.
- Papadopoulos, N., McGinley, J., Tonge, B., Bradshaw, J., Saunders, K., Murphy, A., & Rinehart, N. (2012). Motor proficiency and emotional/behavioural disturbance in autism and Asperger's disorder: Another piece of the neurological puzzle? *Autism*, 16, 627-640.
- Paquet, A., Olliac, B., Golse, B., & Vaivre-Douret, L. (2015). Current knowledge on motor disorders in children with autism spectrum disorder (ASD). *Child Neuropsychology*, 1-32. Advance online publication.

- Pasini, A., D'Agati, E., Pitzianti, M., Casarelli, L., & Curatolo, P. (2012). Motor examination in children with attention deficit/hyperactivity disorder and Asperger syndrome. *Acta Paediatrica*, 101, e15-e18.
- Petermann F. (2008). *Movement Assessment Battery for Children* (2nd ed.). Frankfurt, Germany: Pearson Assessment.
- Provost, B., Lopez, B., & Heimerl, S. (2007). A comparison of motor delays in young children: Autism spectrum disorder, developmental delay, and developmental concerns. *Journal of Autism and Developmental Disorders*, 37, 321-328.
- Remscheid, H., & Kamp-Becker, I. (2007): Das Asperger Syndrom, eine Autismus-Spektrum-Störung. *Deutsches Ärzteblatt*, 104, 873-882.
- Rinehart, N. J., Tonge, B. J., Bradshaw, J. L., Iansek, R., Enticott, P. G., & McGinley, J. (2006). Gait function in high-functioning autism and Asperger's disorder. *European Child & Adolescent Psychiatry*, 15, 256-264.
- Rinehart, N. J., Tonge, B. J., Iansek, R., McGinley, J., Brereton, A. V., Enticott, P. G., & Bradshaw, J. L. (2006). Gait function in newly diagnosed children with autism: Cerebellar and basal ganglia related motor disorder. *Developmental Medicine & Child Neurology*, 48, 819-824.
- Segawa, M., & Nomura, Y. (1991). Pathophysiology of human locomotion: Studies on clinical cases. In M. Shimamura, S. Grillner, & V. R. Edgerton (Eds.), *Neurobiological basis of human locomotion* (pp. 317-328). Tokyo, Japan: Japan Scientific Societies.
- Shaw, P., Eckstrand, K., Sharp, W., Blumenthal, J., Lerch, J. P., Greenstein, D. E. E. A., ... Rapoport, J. L. (2007). Attention-deficit/hyperactivity disorder is characterized by a delay in cortical maturation. *Proceedings of the National Academy of Sciences of the United States of America*, 104, 19649-19654.

- Shaw, P., Malek, M., Watson, B., Sharp, W., Evans, A., & Greenstein, D. (2012). Development of cortical surface area and gyrification in attention-deficit/hyperactivity disorder. *Biological Psychiatry*, 72, 191-197.
- Shetreat-Klein, M., Shinnar, S., & Rapin, I. (2014). Abnormalities of joint mobility and gait in children with autism spectrum disorders. *Brain and Development*, 36, 91-96.
- Størvold, G. V., Aarethun, K., & Bratberg, G. H. (2013). Age for onset of walking and prewalking strategies. *Early Human Development*, 89, 655-659.
- Teitelbaum, O., Benton T., Shah, P., Prince A., Kelly J., & Teitelbaum, P. (2004). Eshkol-Wachman movement notation in diagnosis: The early detection of Asperger's syndrome. *Proceedings of the National Academy of Sciences of the United States of America*, 101, 11909-11914.
- Teitelbaum, P., Teitelbaum, O., Nye, J., Fryman, J., & Maurer, R. (1998). Movement analysis in infancy may be useful for early diagnosis of autism. *Proceedings of the National Academy of Sciences of the United States of America*, 95, 13982-13987.
- Thorpe, D. E., Dusing, S. C., & Moore, C. G. (2005). Repeatability of temporospatial gait measures in children using the GAITRite electronic walkway. *Archives of Physical Medicine and Rehabilitation*, 86, 2342-2346.
- Van Damme, T., Simons, J., Sabbe, B., & van West, D. (2015). Motor abilities of children and adolescents with a psychiatric condition: A systematic literature review. *World Journal of Psychiatry*, 5, 315-329.
- Vernazza-Martin, S., Martin, N., Vernazza, A., Lepellec-Muller, A., Rufo, M., Massion, J., & Assaiante, C. (2005). Goal directed locomotion and balance control in autistic children. *Journal of Autism and Developmental Disorders*, 35, 91-102.
- Vilensky, J. A., Damasio, A. R., & Maurer, R. G. (1981). Gait disturbances in patients with autistic behavior: A preliminary study. *Archives of Neurology*, 38, 646-649.

- Wagner, M. O., Macha, T., Kastner, J., Petermann, F., Jekauc, D., Worth, A., & Bös, K. (2011). Frühdiagnostik motorischer Funktionen. [Early diagnosis of motor function]. *Diagnostica*, 57, 225-233.
- Weiss, M. J., Moran, M. F., Parker, M. E., & Foley, J. T. (2013). Gait analysis of teenagers and young adults diagnosed with autism and severe verbal communication disorders. *Frontiers in Integrative Neuroscience*, 7.
- World Health Organization. (1992). *The ICD-10 classification of mental and behavioural disorders: clinical and diagnostic guidelines*. Geneva, Switzerland: World Health Organization.
- Zilbovicius, M., Garreau, B., Samson, Y., Remy, P., Barthelemy, C., Syrota, A., & Lelord, G. (1995). Delayed maturation of the frontal cortex in childhood autism. *American Journal of Psychiatry*, 152, 248-252.

Figure captions

Fig. 1 Associations of M-ABC-2 overall score (normative mean = 10, standard deviation = 3) and gait variability (a: stride velocity; b: stride time; c: stride length) for children with autism spectrum disorder (ASD) and controls. Standardized regression coefficients (β) and p values are presented next to the slopes. M-ABC-2 = Movement Assessment Battery for Children, 2nd edition. CV = Coefficient of variation

Fig. 2 Associations of age and gait variability (a: stride velocity; b: stride time; c: stride length) for children with autism spectrum disorder (ASD) and controls. Standardized regression coefficients (β) and p values are presented next to the slopes. CV = Coefficient of variation

Table 1

Demographic characteristics of children with autism spectrum disorder (ASD) and controls

Characteristic	ASD ($n = 32$) ^a	Controls ($n = 36$)	p
Age (years)	9.2 (3.8)	9.0 (3.8)	.81
Sex (girls:boys)	5:27	5:31	.84
Height (cm)	131.4 (41.2)	136.4 (22.0)	.52
Weight (kg)	39.7 (21.9)	33.4 (16.5)	.19
Leg length (cm) ^b	74.1 (16.2)	72.7 (14.6)	.71

Note. Data are mean (SD) or number; p values are given for independent t test or χ^2 test.

^aNine patients (Ps) were medicated: P1, sultiame and levetiracetam; P2, P3, melatonin; P4–P7, risperidone; P8, risperidone and melatonin; P9, methylphenidate.

^bLeg length was measured with footwear from greater trochanter to the floor, bisecting the lateral malleolus.

Table 2

Statistical results from the MANOVAs comparing gait measures (spatiotemporal and variability measures), motor milestones, and general motor skills of children with autism spectrum disorder (ASD) and controls

Measures	ASD	Controls	<i>F</i>	<i>p</i>	η^2
<i>Gait measures</i>					
Velocity (cm/s)	126.95 (31.19)	124.15 (17.58)	0.214	.645	.003
Stride time (s)	0.99 (0.20)	0.98 (0.11)	0.089	.767	.001
Stride length (cm)	119.71 (20.68)	121.25 (19.90)	0.098	.755	.001
Base of support (cm)	10.47 (2.40)	8.40 (1.85)	16.049	<.001	.196
CV stride velocity (%)	6.42 (3.99)	3.65 (2.07)	13.246	.001	.167
CV stride time (%)	5.05 (3.42)	2.54 (1.18)	17.259	<.001	.207
CV stride length (%)	4.95 (2.79)	2.92 (1.58)	13.921	<.001	.174
<i>Motor milestones</i>					
Sit upright autonomously (months)	8.08 (3.96)	7.30 (1.31)	1.108	.297	.020
Walk autonomously (months)	16.37 (6.23)	13.31 (1.23)	6.725	.012	.111
<i>General motor skills</i>					
M-ABC-2 overall score ^a	4.80 (2.19)	10.89 (2.59)	78.378	<.001	.597
Manual dexterity	4.45 (2.82)	9.54 (2.81)	38.155	<.001	.419
Ball skills	6.08 (2.57)	10.89 (3.66)	30.238	<.001	.363
Balance	6.85 (2.54)	11.75 (2.38)	50.270	<.001	.487

Note. Data are mean (*SD*), *F* statistics, *p* values, and effect size (η^2). ^aStandard score normative mean = 10, standard deviation = 3. CV = Coefficient of variation. M-ABC-2 = Movement Assessment Battery for Children, 2nd edition.

Table 3

Hierarchical regressions with Group \times Motor milestones (2a, b), Group \times Motor skills (2c), and Group \times Age (2d) interactions predicting gait variability measures

Predictor	CV stride velocity	CV stride time	CV stride length
<i>Step 1</i>			
Leg length	-.396*	-.386*	-.463**
Group (ASD vs. control)	-.462**	-.515**	-.502**
F of total model	.10.067*	9.462*	14.732**
<i>Step 2a</i>			
Sit upright autonomously	-.034	-.057	-.085
Group (ASD vs. control) \times sit upright autonomously	.125	.113	.095
F change of interaction	.569	.501	.390
F of total model	7.616**	9.061**	11.122**
<i>Step 2b</i>			
Walk autonomously	-.135	-.038	-.058
Group (ASD vs. control) \times walk autonomously	-.131	-.093	-.289
F change of interaction	.266	.141	1.471
F of total model	8.092**	9.354 **	11.132**
<i>Step 2c</i>			
M-ABC-2 overall score	-.423*	-.350*	-.375*
Group (ASD vs. control) \times M-ABC-2 overall score	.310*	.315*	.254*
F change of interaction	6.322*	6.428*	4.336*
F of total model	12.065**	11.604**	12.608**
<i>Step 2d</i>			
Age	-.529*	-.566*	-.541*
Group (ASD vs. control) \times age	.197*	.269**	.207*
F change of interaction	4.715*	10.086**	6.011*
F of total model	14.620**	19.269**	19.512**

Coefficients are standardized regression coefficients unless otherwise indicated. Sex: -1 = boy; +1 = girl. Group: -1 = ASD; +1 = control. ASD = Autism spectrum disorder. M-ABC-2 = Movement Assessment Battery for Children, 2nd edition. CV = Coefficient of variation.

* $p \leq .05$; ** $p \leq .001$

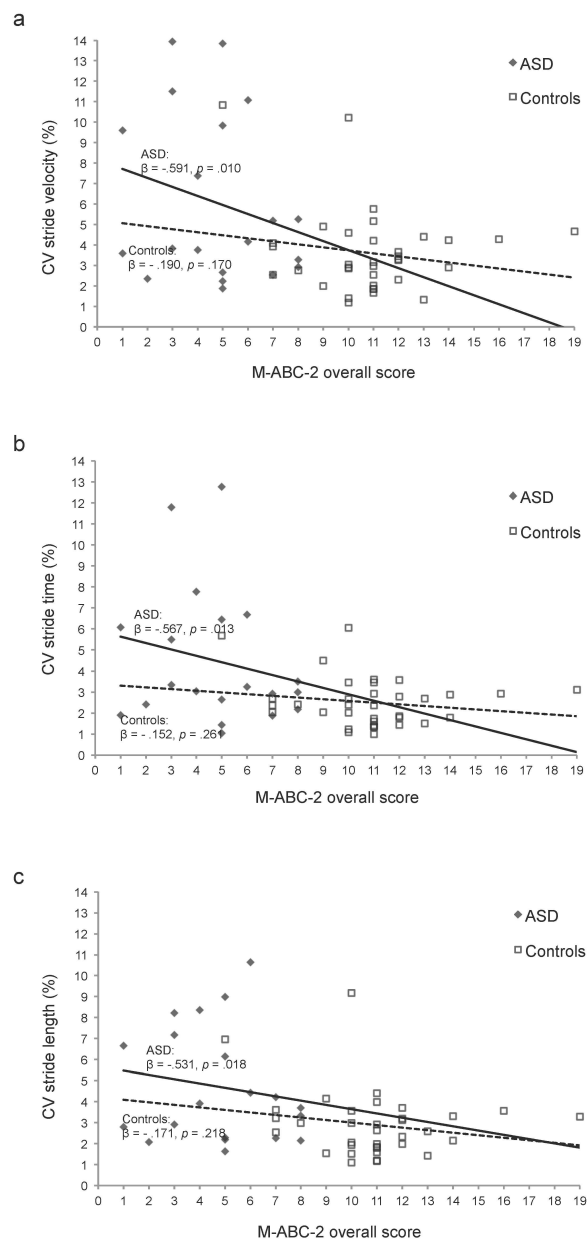


Fig. 1

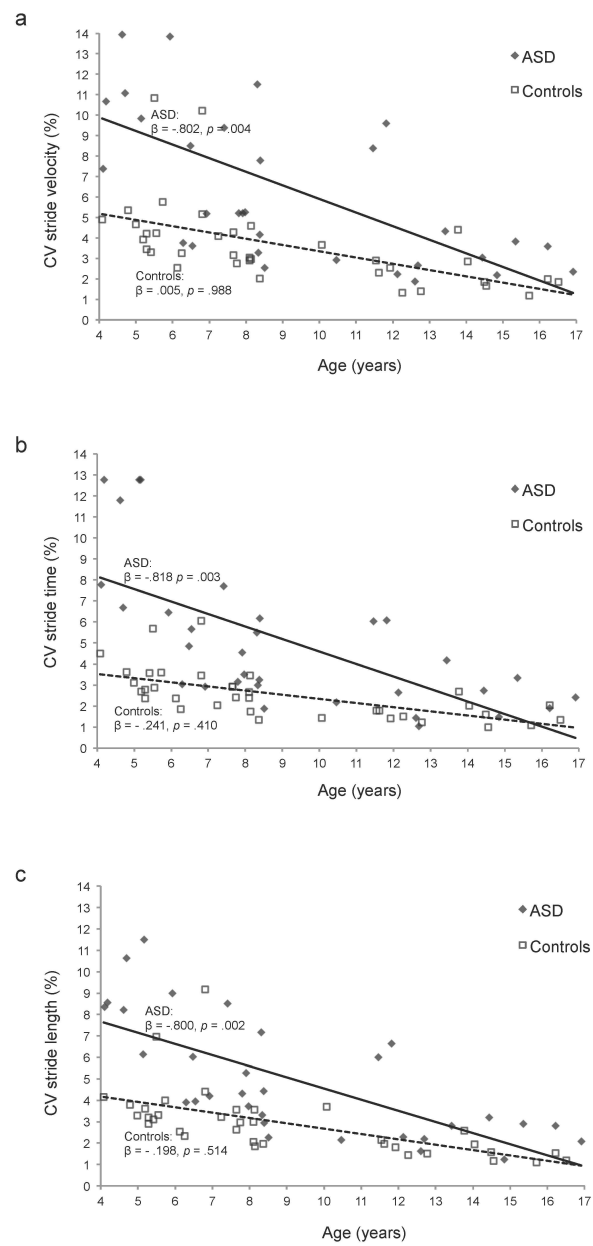


Fig. 2

APPENDIX D: Article 4

Manicolo, O., Grob, A., Lemola, S., & Hagmann-von Arx, P. (2016). Age-related decline of gait variability in children with attention-deficit/hyperactivity disorder: Support for the maturational delay hypothesis in gait. *Gait and Posture*, 44, 245-249.



Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Age-related decline of gait variability in children with attention-deficit/hyperactivity disorder: Support for the maturational delay hypothesis in gait



Olivia Manicolo*, Alexander Grob, Sakari Lemola, Priska Hagmann-von Arx

Department of Psychology, University of Basel, Basel, Switzerland

ARTICLE INFO

Article history:

Received 9 October 2015

Received in revised form 12 November 2015

Accepted 9 December 2015

Keywords:

Gait variability

ADHD

Children

Maturational delay

ABSTRACT

Background: Previous findings showed a tendency toward higher gait variability in children with attention-deficit/hyperactivity disorder (ADHD) compared to controls. This study examined whether gait variability in children with ADHD eventually approaches normality with increasing age (delay hypothesis) or whether these gait alterations represent a persistent deviation from typical development (deviation hypothesis).

Method: This cross-sectional study compared 30 children with ADHD (25 boys; $M_{age} = 10$ years 11 months, range 8–13 years; $n = 21$ off medication, $n = 9$ without medication) to 28 controls (25 boys; $M_{age} = 10$ years 10 months, range 8–13 years). Gait parameters (i.e. velocity and variability in stride length and stride time) were assessed using an electronic walkway system (GAITRite) while children walked at their own pace.

Results: Children with ADHD walked with significantly higher variability in stride time compared to controls. Age was negatively associated with gait variability in children with ADHD such that children with higher age walked with lower variability, whereas in controls there was no such association.

Conclusions: Children with ADHD displayed a less regular gait pattern than controls, indicated by their higher variability in stride time. The age-dependent decrease of gait variability in children with ADHD showed that gait performance became more regular with age and converged toward that of typically developing children. These results may reflect a maturational delay rather than a persistent deviation of gait regularity among children with ADHD compared to typically developing children.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Attention deficit/hyperactivity disorder (ADHD) – one of the most frequently diagnosed disorders in childhood – is characterized by symptoms of age-inappropriate impulsivity, hyperactivity, and inattention [1]. Additionally, many studies have demonstrated that children with ADHD show deficits in executive functions [2], that is, higher cognitive processes including the control and allocation of attentional resources necessary for adaptive planning of behavior [3]. Supporting findings stem from structural and functional neuroimaging studies with children with ADHD showing reduced volumes and metabolic rates in specific brain

areas including the frontal lobe, which plays an important role in executive function and attention [4].

Gait forms an important and highly complex mode of human locomotion involving neural control systems to produce coordinated muscle firings and limb movements [5]. After children attain independent walking, their gait steadily matures, with steps becoming straighter, longer, and narrower [6]. While some argue that children reach a mature walking pattern at about 7 years [7], recent evidence suggests that gait continues to develop during late childhood and adolescence [8]. For many years mature gait was viewed as a largely automated motor task involving little cognitive input but it is now generally acknowledged that executive and attentional functions are involved in the control of gait [9].

Previous studies showed that gait variability, the stride-to-stride fluctuations in walking, is closely linked to executive functions such that poor performance in executive functions is associated with increased gait variability among healthy older adults as well as patients suffering from neurological disease

* Corresponding author at: Department of Psychology, University of Basel, Missionsstrasse 62, 4055 Basel, Switzerland. Tel.: +41 061 267 06 30; fax: +41 061 267 06 61.

E-mail address: olivia.manicolo@unibas.ch (O. Manicolo).

[10]. However, although problems with executive functions and attention are among the core ADHD symptoms, research on gait in children with ADHD is scarce. So far two studies have investigated gait in children with ADHD (off or without medication) [11,12]: One [11] measured gait characteristics of children with ADHD ($n = 16$; $M_{\text{age}} = 11$ years 11 months) and controls using footswitches, and the other [12] used the GAITRite walkway system to measure gait performance in children with ADHD ($n = 14$; $M_{\text{age}} = 10$ years 10 months). Whilst the former explored a temporal measure of gait variability by investigating stride time variability [11], the latter investigated both temporal (e.g., variability in cadence) and spatial measures of gait variability such as stride length variability [12]. While no group differences were found for spatial measures of gait variability [12], both studies found that children with ADHD showed a tendency toward higher values in temporal measures of gait variability compared to controls ($p = .070$ [12] and $p = .090$ [11]). As increased gait variability is assumed to reflect inconsistent stepping patterns and reduced gait regularity during walking [5], these findings lend preliminary support that children with ADHD show a less regular gait pattern compared to controls.

In the context of research on ADHD, there is ongoing debate on whether reported deficits in children with ADHD result from a maturational delay or instead, a persistent deviance from typical development [13,14]. The maturational delay hypothesis states that children with ADHD lag behind in their maturational process but eventually approach normality with increasing age [13]. This hypothesis is supported by the finding that ADHD symptoms tend to improve with age and that up to 80% of children outgrow ADHD in adulthood [15]. Furthermore, a study on brain development in 223 children with ADHD showed that in 50% of these children, the cortex reached maximum thickness only at age 10 years 6 months as opposed to 7 years 6 months among children without ADHD. These results imply that the brain of children with ADHD matures about 3 years later compared to typically developing controls [14].

In contrast, the maturational deviation hypothesis proposes that individuals with ADHD do not necessarily lag behind in their maturational process but show stable deviation from typical development across age [13]. This hypothesis was initially built on an early neurodevelopmental study including quantitative electroencephalography (EEG) showing that in a sample of 353 children with symptoms of hyperactivity, 90% had abnormalities in their EEGs. When the EEGs were examined within age groups, the percentage of slowing of the EEG did not increase or decrease with increasing age and therefore did not show any maturational process, which was interpreted as support for the developmental deviation hypothesis [16]. Meanwhile, this hypothesis found further support from longitudinal studies, providing evidence for the continuation of ADHD into adulthood by reporting persistent symptoms of inattention, disorganization, distractibility, and impulsivity [17]. However, there is also conflicting evidence with other studies reporting only little persistence of ADHD symptoms into adult years [18], which is possibly due to differences in methodology. Taken together, the evidence for a persistent deviation from typical development involving continuation of ADHD from childhood to adulthood remains equivocal.

In sum, results from two previous studies show a tendency toward higher temporal measures of gait variability in children with ADHD compared to typically developing controls [11,12]. However, the sample sizes in both studies were small, which may have limited their power to detect statistically significant group differences. Therefore, we aimed to investigate gait variability in a larger sample of children with ADHD than previously studied. Furthermore, to our knowledge, gait performance in children with ADHD has not been investigated in the context of the ongoing maturational delay versus maturational

deviation debate. Hence, our main goal was to investigate age-dependent alterations in gait variability among children with ADHD compared to typically developing controls.

Building on this background, we (1) hypothesized that temporal measures of gait variability in children with ADHD would be higher than in controls and (2) investigated whether gait variability in children with ADHD decreases with increasing age toward that of typically developing children (reflecting a maturational delay) or remains persistent and nonconvergent toward controls across age (reflecting a maturational deviation).

2. Methods

2.1. Participants

Children with ADHD were recruited from privately practicing pediatricians and the University Children's Hospital Basel, Switzerland. The inclusion criteria comprised an ADHD diagnosis according to the DSM-IV or ICD-10. The study sample comprised 30 children diagnosed with ADHD (25 boys and 5 girls, $M_{\text{age}} = 10$ years 11 months, range 8–13 years) not selected on the basis of subtype. The diagnosis of ADHD was confirmed by the Conners' Parent Rating Scale [19]. The majority of participants with ADHD ($n = 21$) were on stimulant medication such as methylphenidate (Ritalin[®], Novartis Pharmaceuticals Corporation). Following recommendations by Thompson [20], medicated children discontinued medication at least 24 h before testing. Group comparisons showed that ADHD children off medication and without medication did not differ on any variable included in this study (i.e., all p values $> .09$ for demographics, motor skills, and gait parameters; data not shown). A control group of 28 typically developing children (25 boys and 3 girls, $M_{\text{age}} = 10$ years 10 months, range 8–13 years) was recruited from local schools. Exclusion criterion for controls was a diagnosis of developmental psychopathology. This was confirmed by parental questionnaire in which information on developmental, medical, and psychiatric history was obtained (i.e. whether children had any previous diagnoses or had received any intervention). Controls were screened for ADHD symptoms using the Conners' Parent Rating Scale [19] and all were within the normal limits and of no clinical concern.

The intellectual functioning of all participating children was assessed using the German version of the Wechsler Intelligence Scale for Children, 4th edition (WISC-IV) [21] and all children were screened for developmental coordination disorder (DCD) using the German version of the Movement Assessment Battery for Children, 2nd edition (M-ABC-2) [22] with a cut-off < 16 th percentile [22]. None of the children were excluded because of intellectual impairment ($IQ < 70$) or being at risk for DCD.

The local Ethics Committee approved the study. Parents gave written informed consent for the children to participate and assent was obtained from the children.

2.2. Procedure and measures

Gait was measured using the GAITRite system (GAITRite Platinum; CIR Systems, USA) consisting of a 701-cm-long walkway with 23,040 integrated pressure sensors. A 1.25-m nonrecordable zone was added at each end to minimize acceleration and deceleration effects. Therefore, children walked approximately 10 m per walk comprising on average 8 steps. The validity and reliability of gait assessment using GAITRite for children is well established [23].

The following gait parameters were evaluated: velocity (obtained by dividing the distance traveled by ambulation time, expressed in centimeters per second), and gait variability, assessed as stride-to-stride variability in stride length and stride time, expressed as the percentage coefficient of variation ($CV = \text{standard}$

deviation/mean $\times 100$). While velocity as a general indicator of functional performance is the most commonly reported gait outcome [24], gait variability provides a more discriminant and sensitive measure of subtle changes in gait performance and reflects the regularity of gait [5].

Height and weight were measured prior to gait assessment. Then, children were given one demonstration trial and a practice trial before performing four walking trials. Children were instructed to walk at their own pace. After each walk, data were analyzed using GAITRite software. Gait parameters were averaged over the trials for further data analysis.

Because previous research showed associations of ADHD with poorer motor performance [25], we additionally assessed motor skills to control for possible differences between children with and without ADHD. These skills were assessed using the German version of the M-ABC-2 [22], an individually administered standardized measure of motor function for children 3–16 years old with established reliability and validity [26]. The M-ABC-2 comprises three age-related item sets, each consisting of eight tasks measuring manual dexterity, aiming and catching, and balance. Item scores can be combined to form an overall score with a normative mean = 10 and standard deviation = 3, which was used in our analyses. An overall score <16th percentile is indicative of suspected DCD [22].

2.3. Statistical analysis

To test for group differences in demographics and motor skills, we used the χ^2 test for categorical variables or the independent-sample *t* test for continuous variables. Results indicated a group difference for motor skills, so motor skills (i.e. M-ABC-2 overall score) were included a priori as a covariate in the following group comparisons. Analysis of covariance (ANCOVA) was used to test for group differences on gait parameters. *P* values and effect sizes (Cohen's *d*) are reported. If an extreme value (defined as a score exceeding 3 SDs from the group mean) occurred in the gait parameters, scores were truncated to ± 3 SD. To analyze whether associations between age and gait parameters differed in children with ADHD and controls (i.e. whether group [ADHD vs. control] acted as a moderator of these associations), hierarchical regression analyses were conducted following the procedure proposed by Aiken and West [27]. Control variables (i.e. motor skills, sex, height, weight) were entered in a first block. Group (ADHD vs. control) and age were entered in the next block. Finally, the interaction terms between group (ADHD vs. control) and age were entered in the last block. If a significant interaction was found (indicating a significant moderation effect), then the interaction was graphed by computing the predicted gait parameters by age separately for children with ADHD and controls.

Separate multiple regression analyses were used to evaluate whether the slopes in the graphs were significantly different from zero [27].

3. Results

Table 1 provides an overview of the demographics, motor skills, and gait parameters of the children with ADHD and controls. The groups were similar with respect to sex, age, height, and weight. Significant group differences were found for motor skills, with children with ADHD showing a lower group mean for the M-ABC-2 overall score than controls, $t(56) = -3.82$, $p < .01$, $d = .99$. Results from ANCOVAs controlling for motor skills showed that children with ADHD and controls had similar velocity, $F(1,55) = 0.09$, $p = .769$, $d = .08$, and variability in stride length, CV stride length: $F(1,55) = 1.19$, $p = .280$, $d = .44$, whereas the two groups differed significantly in stride time variability, CV stride time: $F(1,55) = 4.25$, $p = .044$, $d = .57$, such that children with ADHD walked with higher variability than controls.

Hierarchical regression analyses were first calculated for the combined participant sample. After controlling for sex, height, weight, motor skills, and group, children's age was significantly associated with higher velocity ($\beta = .337$, $p = .029$) and lower gait variability (CV stride length: $\beta = -.302$, $p = .036$; CV stride time: $\beta = -.439$, $p = .001$). In addition, moderated hierarchical regression analyses were calculated with group \times age interaction terms, controlling for sex, height, weight, motor skills, group, and age (Table 2). These analyses revealed significant group \times age interactions for both gait variability measures: Group moderated the association between age and CV stride length ($\beta = .353$, $p = .004$) and the association between age and CV stride time ($\beta = .279$, $p = .014$). As shown in Fig. 1, in children with ADHD, age was significantly associated with CV stride length ($\beta = -.550$, $p = .007$) and CV stride time ($\beta = -.642$, $p = .003$), such that increasing age was related to lower gait variability, whereas in controls there was no significant association between age and CV stride length ($\beta = -.002$, $p = .992$) and CV stride time ($\beta = -.319$, $p = .127$).

4. Discussion

We investigated gait differences in children with ADHD and controls and analyzed whether differences in gait variability decrease or remain stable with increasing age. Two previous studies indicated no group differences in velocity and spatial measures of gait variability but a tendency toward higher variability in temporal measures of gait variability among children with ADHD (off or without medication) [11,12]. We focused on these gait parameters in our study and tried to reinforce these

Table 1
Demographics, motor skills, and gait parameters of children with attention-deficit/hyperactivity disorder (ADHD) and controls.

Sample characteristic	ADHD (<i>n</i> = 30)	Controls (<i>n</i> = 28)	<i>p</i> ^a	Effect size ^b
Demographics				
Sex (girls:boys)	5:25	3:25	0.51	0.09
Age (years)	10.90 (1.45)	10.83 (1.43)	0.85	0.05
Height (cm)	142.69 (29.67)	140.32 (29.34)	0.76	0.08
Weight (kg)	40.37 (16.81)	36.81 (12.01)	0.36	0.02
Motor skills				
M-ABC-2 overall score ^c	9.33 (1.86)	11.25 (2.00)	<0.01	0.99
Gait parameters				
Velocity (cm/s)	127.75 (21.76)	131.51 (15.64)	0.77	0.08
CV stride length (%)	2.28 (1.13)	1.88 (0.61)	0.28	0.44
CV stride time (%)	2.45 (1.50)	1.67 (0.55)	0.04	0.57

Data are mean (SD) or number.

^a *P* values of the χ^2 test (sex), *t* test (age, height, weight, motor skills) or analysis of covariance (gait parameters) controlled for motor skills.

^b Effect size for sex (girls:boys) is phi; for all other variables effect size is Cohen's *d*.

^c Standard score normative mean = 10, standard deviation = 3. M-ABC-2 = Movement Assessment Battery for Children, 2nd edition.

CV, coefficient of variation.

Table 2
Hierarchical regressions with group \times age interactions predicting gait parameters.

Predictors	Gait parameter		
	Velocity	CV stride length	CV stride time
Step 1			
Sex	-.180	.137	.088
Height	-.028	-.041	.073
Weight	-.008	-.233	-.286
Motor skills	.156	-.204	-.236
R ² of total model	.051	.140	.115
Step 2			
Group (ADHD vs. control)	.055	-.215	-.338 [*]
Age	.337 [*]	-.302 [*]	-.439 ^{**}
ΔR^2 step 2	.088	.105 [*]	.234 ^{**}
R ² of total model	.139	.245	.349
Step 3			
Group (ADHD vs. control) \times age	-.161	.353 [*]	.279 [*]
ΔR^2 step 3	.025	.119	.074
R ² of total model	.164	.364	.423

Coefficients are standardized regression coefficients if not otherwise indicated. Step 1: model with control variables predicting gait parameters. Step 2: model with group and age as predictors for gait parameters, controlled for variables entered in step 1. Step 3: Group \times age interaction term as predictor for gait parameters, controlled for variables entered in step 1 and step 2. Sex: -1 = girl; +1 = boy. Group: -1 = ADHD; +1 = control. ADHD = Attention-deficit/hyperactivity disorder. CV, coefficient of variation.

^{*} $p \leq .05$.

^{**} $p \leq .001$.

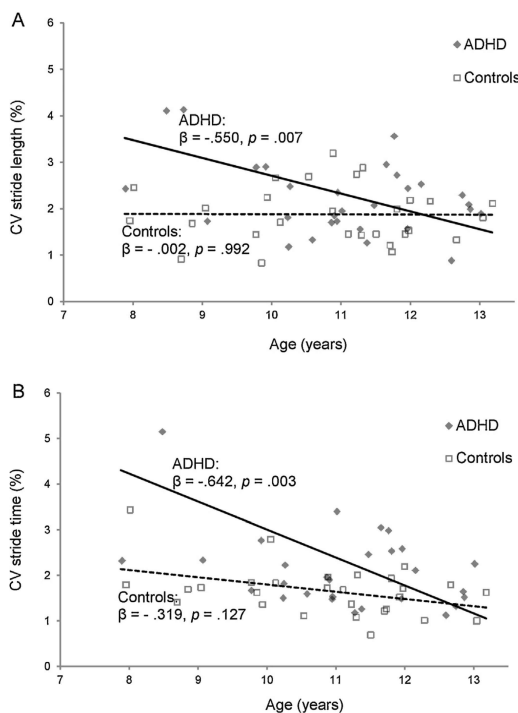


Fig. 1. Associations of age and gait variability (A: stride length; B: stride time) for children with attention-deficit/hyperactivity disorder (ADHD) and controls. Standardized regression coefficients (β) and p values are presented next to the slopes. CV, coefficient of variation.

previous findings by investigating a larger sample. In line with the two previous studies [11,12], we found that children with ADHD showed similar velocity and similar stride length variability but significantly higher variability in stride time than controls when walking at their own pace. These results lend support to the notion of a less regular walking pattern in children with ADHD compared to typically developing controls and support the suggestion that measures of variability may provide a more discriminant and sensitive measure of gait performance than other parameters such as velocity [5].

As gait variability was linked to executive functions in adult samples [10], deficits in executive function and the impaired attentional capacity associated with ADHD [2] may have contributed to the alterations in gait variability among children with ADHD in our study. However, also deeper brain structures such as the basal ganglia and the cerebellar vermis are known to be involved in the regulation of locomotor activity [28] often referred to as “motor control” [11]. Thus, the here reported alterations in gait variability might not only be related to executive and attentional functions associated with frontal brain regions [4] but also to subcortical motor structures. After all, it remains subject to future research to explore potential underlying mechanisms and the origins of the neural control related to gait variability in children with ADHD.

Further, we found that age was associated with all gait measures such that with increasing age velocity increased whereas variability in stride length and stride time decreased. These results support the suggestion that gait continues to develop across childhood [8]. Additionally, children with ADHD displayed an age-dependent decrease of their gait variability toward that of controls, lending support for the maturational delay hypothesis, which assumes that children with ADHD lag behind in their development but eventually approach normality with increasing age [13]. Further support for this hypothesis stems from neurodevelopment findings [14]. These results revealed that children with ADHD show a delay in brain maturation – particularly in prefrontal regions important for cognitive processes, including executive functions and attention, and also for motor planning – but that brain maturation eventually converges toward typically developing controls. Interestingly, the primary motor cortex, which is involved in the initiation and execution of movement, was the only cortical area where children with ADHD showed slightly earlier maturation than controls. Shaw and colleagues [14] argued that the combination of early maturation of the primary motor cortex with the later maturation of higher order motor control regions might reflect the poor regulation of motor performance related to ADHD. Since we found an age-dependent decrease in gait variability in children with ADHD toward that of controls, one could hypothesize that this maturational process in gait regularity is associated with a delayed maturation of higher order motor control regions as previously reported by Shaw and colleagues [14]. However, more research is needed to confirm an association between brain maturation and gait regularity.

Our study has strengths and limitations. We consider it a strength that gait was assessed using an objective electronic gait assessment system with proven reliability and validity [23]. Further, we accounted for impaired motor proficiency of children with ADHD when analyzing gait measures and further screened all participating children for DCD to account for possible interference. However, a large percentage of children with ADHD meet diagnostic criteria for DCD [25] and our results cannot be generalized to individuals with a comorbid diagnosis. Additionally, children with ADHD were not classified according to any ADHD subtype and it therefore remains unclear whether gait characteristics differ between subtypes. Furthermore, we analyzed temporal and spatial gait parameters, as the walkway system GAITRite does

not allow the investigation of peculiar walking patterns such as toe walking which has previously been reported for children with ADHD [29]. Finally, our study includes cross-sectional data, whereas direct testing of the maturational delay hypothesis related to gait development in children with ADHD would require longitudinal studies.

In conclusion, our results are the first to lend support for a maturational delay in gait regularity among school-aged children with ADHD, indicated by an age-dependent decrease of their gait variability toward that of typically developing children.

Conflict of interest

The authors declare that there is no conflict of interest.

References

- [1] American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders. 5th ed. Washington, DC: American Psychiatric Association Press; 2013.
- [2] Willcutt EG, Doyle AE, Nigg JT, Faraone SV, Pennington BF. Validity of the executive function theory of attention-deficit/hyperactivity disorder: a meta-analytic review. *Biol Psychiatry* 2005;57:1336–46.
- [3] Anderson V. Executive function in children: introduction. *Child Neuropsychol* 2002;8:69–70.
- [4] Silk T, Vance A, Rinehart N, Egan M, O'Boyle M, Bradshaw JL, et al. Fronto-parietal activation in attention-deficit hyperactivity disorder, combined type: functional magnetic resonance imaging study. *Br J Psychiatry* 2005;187:282–3.
- [5] Adolph KE, Vereijken B, Shrout PE. What changes in infant walking and why. *Child Dev* 2003;74:475–97.
- [6] Holm I, Tvetter AT, Fredriksen PM, Vollestad N. A normative sample of gait and hopping on one leg parameters in children 7–12 years of age. *Gait Posture* 2009;29:317–21.
- [7] Froehle AW, Nahhas RW, Sherwood RJ, Duren DL. Age-related changes in spatiotemporal characteristics of gait accompany ongoing lower limb linear growth in late childhood and early adolescence. *Gait Posture* 2013;38:14–9.
- [8] Lythgo N, Wilson C, Galea M. Basic gait and symmetry measures for primary school-aged children and young adults. II: walking at slow, free and fast speed. *Gait Posture* 2011;33:29–35.
- [9] Woolacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture* 2002;16:1–14.
- [10] Amboni M, Barone P, Hausdorff JM. Cognitive contributions to gait and falls: evidence and implications. *Mov Disord* 2013;28:1520–33.
- [11] Leitner Y, Barak R, Giladi N, Peretz C, Eshel R, Gruendlinger L, et al. Gait in attention deficit hyperactivity disorder: effects of methylphenidate and dual tasking. *J Neurol* 2007;254:1330–8.
- [12] Papadopoulos N, McGinley JL, Bradshaw JL, Rinehart NJ. An investigation of gait in children with Attention Deficit Hyperactivity Disorder: a case controlled study. *Psychiatry Res* 2014;218:319–23.
- [13] Burke A, Edge A. Neurodevelopmental pathways of childhood ADHD into adulthood: maturational lag, deviation, or both? Intech 2013. <http://dx.doi.org/10.5772/53865>.
- [14] Shaw P, Eckstrand K, Sharp W, Blumenthal J, Lerch JP, Greenstein D, et al. Attention deficit/hyperactivity disorder is characterized by a delay in cortical maturation. *Proc Natl Acad Sci U S A* 2007;104:19649–54.
- [15] Faraone S, Biederman J, Mick E. The age dependent decline of attention deficit/hyperactivity disorder: a meta-analysis of follow-up studies. *Psychol Med* 2006;36:159–65.
- [16] Klinkerfuss GH, Lange PH, Weinberg WA, O'Leary JL. Electroencephalographic abnormalities of children with hyperkinetic behavior. *Neurology* 1965;15:883–91.
- [17] Fischer M, Barkley RA. The persistence of ADHD into adulthood: (once again) it depends on whom you ask. *ADHD Rep* 2007;15:7–16.
- [18] Wilens TE, Biederman J, Spencer TS. Attention deficit/hyperactivity disorder across the lifespan. *Annu Rev Med* 2002;53:113–31.
- [19] Conners CK. Conners. 3rd ed. Toronto: Multi-Health Systems; 2008.
- [20] Thompson K. Medicines for Mental Health: The Ultimate Guide to Psychiatric Medication. North Charleston: Book Surge Publishing; 2007.
- [21] Petermann F, Petermann U. Wechsler Intelligence Scale for Children (WISC-IV). Frankfurt, Germany: Pearson Assessment; 2011.
- [22] Petermann F. Movement Assessment Battery for Children. 2nd ed. Frankfurt, Germany: Pearson Assessment; 2008.
- [23] Thorpe DE, Dusing SC, Moore CG. Repeatability of temporospatial gait measures in children using the GAITRite electronic walkway. *Arch Phys Med Rehabil* 2005;86:2342–6.
- [24] Al-Yahya E, Dawes H, Smith L, Dennis A, Howells D, Cockburn J. Cognitive motor interference while walking: a systematic review and meta-analysis. *Neurosci Biobehav Rev* 2011;35:715–28.
- [25] Enck C, Bosscher R, Beek P, Doreleijers T. Gross motor performance and self-perceived motor competence in children with emotional, behavioural, and pervasive developmental disorders: a review. *Dev Med Child Neurol* 2009;51:501–17.
- [26] Wagner MO, Macha T, Kastner J, Petermann F, Jekauc D, Worth A, et al. Frühdiagnostik motorischer Funktionen Early diagnosis of motor function Diagnostica 2011;57:225–33.
- [27] Aiken LS, West SG. Multiple regression: testing and interpreting interactions. London: Sage; 1991.
- [28] Anderson CM, Polcari A, Lowen SB, Renshaw PF, Teicher MH. Effects of methylphenidate on functional magnetic resonance relaxometry of the cerebellar vermis in boys with ADHD. *Am J Psychiatry* 2002;159:1322–8.
- [29] Engström P, Van't Hof I, Tedroff K. Neuropsychiatric symptoms and problems among children with idiopathic toe-walking. *J Pediatr Orthop* 2012;32:848–52.

APPENDIX E: Article 5

Manicolo, O., Grob, A., & Hagmann-von Arx, P. Gait in children with attention-deficit hyperactivity disorder in a dual-task paradigm. *Manuscript submitted for publication to Journal of Attention Disorders.*

Draft March 19, 2016

Running head: GAIT AND DUAL-TASKING IN ADHD

Gait in children with attention-deficit hyperactivity disorder in a dual-task paradigm

Olivia Manicolo, MSc¹, Alexander Grob, PhD¹, Priska Hagmann-von Arx, PhD¹

Affiliation: ¹Department of Psychology, University of Basel, Basel, Switzerland

Corresponding author: Olivia Manicolo, Department of Psychology, University of Basel,
Missionsstrasse 62, 4055 Basel, Switzerland, email: olivia.manicolo@unibas.ch,
phone: +41(0)61 267 06 30, fax: +41(0)61 267 06 61

Running head: GAIT AND DUAL-TASKING IN ADHD

Abstract

Objective: To examine gait in school-aged children with attention-deficit hyperactivity disorder (ADHD) and typically developing controls in a dual-task paradigm. **Method:** Thirty children with ADHD (without or off medication) aged 7 to 13 years and 28 controls walked without an additional task (single-task walking) and while performing a concurrent cognitive or motor task (dual-task walking). Gait was assessed using GAITRite recordings of spatio-temporal and variability gait parameters. **Results:** Compared to single-task walking, dual-tasking significantly altered walking performance of children with and without ADHD, whereby dual-task effects on gait were comparable between the two groups. For both children with ADHD and controls the motor concurrent task had a stronger effect on gait than the cognitive concurrent task. **Conclusions:** Gait in children with and without ADHD is affected in a dual-task paradigm indicating that walking requires executive functions. Future investigations of children's dual-task walking should account for the type of concurrent tasks.

Key words: ADHD, gait, dual-task, executive functions, children

Running head: GAIT AND DUAL-TASKING IN ADHD

Gait in children with attention-deficit hyperactivity disorder in a dual-task paradigm

Attention-deficit hyperactivity disorder (ADHD) is one of the most frequently diagnosed disorders in childhood with a prevalence of 5–10% (Polanczyk & Rhode, 2007). It is characterized by three core symptoms: impulsivity, hyperactivity, and inattention (American Psychiatric Association; APA, 2013) and has repeatedly been linked to deficits in executive functions (e.g., Gilberg, 2003; Steger et al., 2001; Wildings, 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Furthermore, children diagnosed with ADHD are at higher risk for fine and gross motor impairments (Kaiser, Schoemaker, Albaret, & Geuze, 2015). Regarding gross motor skills, they are often described as clumsy, having poor motor coordination, and showing more difficulties in static and dynamic balance than typically developing children (Fliers et al., 2010; Racine, Majnemer, Shevell, & Snider, 2008; Shum & Pang, 2009). Additionally, children with ADHD are more likely to show poor performance in physical education classes and are more prone to injuries, such as being struck by an object (Pastor & Reuben, 2006).

However, while many studies investigated motor performance including movement skills, motor coordination, balance as well as physical fitness in children with ADHD (e.g., Buderath et al., 2009; Harvey & Reid, 1997, 2003; Piek, Pitcher, & Hay, 1999; Raberger & Wimmer, 2003), far less is known regarding their walking pattern, a functionally highly relevant aspect of motor performance. So far, three studies have investigated spatiotemporal and variability measures of gait in school-aged children with ADHD (without or off medication) using instrumented gait analysis techniques such as electronic walkway systems or electronic footswitches (Leitner et al., 2007; Manicolo, Grob, Lemola, & Hagmann-von Arx, 2016; Papadopoulos, McGinley, Bradshaw, & Rinehart, 2014). Their results consistently indicated increased gait variability (i.e., stride-to-stride fluctuations) for children with ADHD com-

Running head: GAIT AND DUAL-TASKING IN ADHD

pared to controls while no group differences were found for spatiotemporal gait measures such as velocity (Leitner et al., 2007; Manicolo et al., 2016; Papadopoulos et al., 2014). As increased gait variability is assumed to reflect more inconsistent stepping patterns during walking (Hausdorff, 2005), those findings indicate a less regular gait pattern of school-aged children with ADHD compared to controls.

However, in everyday life children usually do things concomitantly while walking such as listening to someone talk or fastening their jacket buttons. Previous research has shown that such dual-task situations alter children's walking performance (Boonyong, Siu, van Donkelaar, Chou, & Woollacott, 2012; Cherng, Liang, Hwang, & Chen, 2007; Hagmann-von Arx et al. 2015; Huang, Mercer, & Thorpe, 2003; Hung, Meredith, & Gill, 2013; Schaefer, Lövdén, Wieckhorst, & Lindenberger., 2010), indicating that the regulation of gait is not a fully automatic activity but rather requires cognitive control such as executive functions (Woollacott & Shumway-Cook, 2002). Executive functions refer to higher cognitive processes that include the control and allocation of attentional resources necessary for adaptive planning of behaviors (Anderson, 2002). The ability to divide attention (as required in dual-task paradigms) may also be considered an example of an executive function task (Springer et al., 2006). In this vein, studies including clinical adult samples characterized by impaired executive functions (e.g., Alzheimer's or Parkinson's disease) reported poorer gait performance in the clinical samples compared to healthy controls in dual-task conditions (Sheridan, Solomont, Kowall, & Hausdorff, 2003; Yogev et al., 2005). Further, healthy older adults show lower performance in executive functions compared to young adults (Glisky, 2007) what in turn may negatively affect their task performance in dual-task conditions where attention needs to be divided between concurrent tasks (Beurskens & Bock, 2012; Tsang, 2013). Therefore, it is assumed that impaired executive functions contribute to strong-

Running head: GAIT AND DUAL-TASKING IN ADHD

er effects of dual-tasking on gait by limiting the ability to devote the appropriate amount of attention towards walking when simultaneously performing another task (Hausdorff, 2005).

Although ADHD has repeatedly been linked to deficits in executive functions (e.g., Gilberg, 2003; Steger et al., 2001; Wildings, 2005; Willcutt et al., 2005), little is known regarding the role that those limitations may play in dual-task gait in children with ADHD. To our knowledge, so far one study has investigated walking patterns of children with ADHD in a dual-task paradigm. Leitner et al. (2007) measured gait in a dual-task condition where children were instructed to walk and simultaneously listen to a text on tape and count how many times a keyword appeared. Within-group comparisons showed that children with ADHD as well as controls walked with reduced velocity and a tendency toward increased stride time in the dual-task condition compared to normal walking, implying that in both groups gait requires executive functions. Furthermore, between-group comparisons showed that in the dual-task condition both groups walked with similar gait variability, velocity and stride time. Therefore, the effect of dual-tasking on gait was comparable between children with and without ADHD, although it may have been assumed that children with ADHD would show lower gait performance (i.e., lower gait velocity and higher gait variability) compared to controls when their impaired executive functions are additionally taxed by a concurrent task (Leitner et al., 2007). However, the sample studied by Leitner et al. (2007) was rather small, limiting the power of these analyses.

Investigations of dual-task effects on gait among typically developing children showed that gait alterations are apparent for both motor and cognitive concurrent tasks and that effects on walking may differ between the two types of concurrent tasks. For example, Cherng et al. (2007) investigated school-aged children while they walked and concurrently performed an easy or a difficult motor (carrying a tray with or without marbles on it) or cognitive (repeating a series of digits forward or backward) task. Compared to single-task walk-

Running head: GAIT AND DUAL-TASKING IN ADHD

ing, both cognitive concurrent tasks as well as the difficult motor concurrent task caused significant gait alterations. Additionally, results showed that the difficult motor concurrent task led to greater gait alterations (i.e., greater decrease in stride length and greater increase in double limb support) compared to the cognitive concurrent tasks. In a similar vein, a recent study conducted by Hagmann-von Arx, Manicolo, Lemola, and Grob (2016) including school-aged children confirmed these findings by showing that gait performance was stronger affected in a motor dual-task condition in which children were asked to fasten and unfasten a shirt button than in a cognitive dual-task condition in which children were asked to listen to and memorize digits while walking.

These findings may be interpreted from the perspective of the multiple-resource model of attention (Wickens, 1991) assuming that two tasks will interfere with each other if they share the same pool of resources. Hence, a cognitive concurrent task might not cause the same amount of gait alterations as a motor concurrent task that shares resources with walking (Yogev-Seligmann, Hausdorff, & Giladi, 2008). To our knowledge, this assumption has so far not been investigated in children with ADHD since Leitner et al. (2007) included a cognitive concurrent task when walking (i.e., listen to a text and count a key word) but no motor concurrent task.

Taken together, previous results showed that children with ADHD (without or off medication) walk with a less regular gait pattern than controls indicated by higher gait variability in single-task walking (Leitner et al., 2007; Manicolo et al., 2016; Papadopoulos et al., 2014). Research on dual-task walking in children with ADHD, however, is scarce. So far, we know of one study showing that a cognitive concurrent task significantly altered gait performance of children with ADHD and that this dual-task effect on gait was comparable between children with and without ADHD (Leitner et al., 2007). Finally, findings for typically developing children showed that the dual-task effects on walking differed between cognitive and

Running head: GAIT AND DUAL-TASKING IN ADHD

motor concurrent tasks with motor concurrent tasks causing stronger gait alterations (Cherng et al., 2007; Hagmann-von Arx et al., 2016). To our knowledge, no study has investigated dual-task gait in children with ADHD while performing a motor concurrent task and none has compared cognitive and motor concurrent task effects on walking in children with ADHD.

The main goal of this study was to investigate gait in children with and without ADHD in a dual-task paradigm including both a concurrent cognitive and motor task condition. First, we expected that a concurrent cognitive and motor task would negatively affect gait performance of children with and without ADHD as there is evidence that gait requires executive functions (e.g., Woollacott & Shumway-Cook, 2002). Second, we expected to find more strongly compromised dual-task gait performance in children with ADHD compared to children without ADHD due to their impaired executive functions (e.g., Beurskens & Bock, 2012; Tsang, 2013; Willcutt et al., 2005). Finally, we expected to find a stronger dual-task effect on gait for the motor concurrent task compared to the cognitive concurrent task in children with and without ADHD drawing on the assumption that tasks sharing the same pool of processing resources interfere with each other more strongly (Yogev-Seligmann et al., 2008).

Methods

Participants

The sample included in this study comprised 30 children with ADHD (25 boys and five girls, $M_{age} = 10.9$ years, age range: 7–13 years, without or off medication) and 28 typically developing controls (25 boys and three girls, $M_{age} = 10.8$ years, age range: 7–13 years) and has been described in a previous study in detail (Manicolo et al., 2016). Children with and without ADHD did not differ in demographics (i.e., age, sex, height, weight, leg length; Table 1). None of the 58 included children were at risk for developmental coordination disorder (DCD) (i.e., $> 16^{\text{th}}$ percentile in the German version of the Movement Assessment Battery for Children 2nd edition) (Petermann, 2008) or intellectual impairment (i.e., $IQ > 70$ as-

Running head: GAIT AND DUAL-TASKING IN ADHD

essed by the German version of the Wechsler Intelligence Scale for Children 4th edition) (Petermann & Petermann, 2011). The Ethics Committee of Basel approved the study protocol. Parents gave written informed consent for the children to participate and assent was obtained from the child.

Please insert Table 1 about here

The previous study (Manicolo et al., 2016) showed, that regarding single-task walking there were no group differences in velocity ($p = .769$, $d = 0.08$) and stride length variability ($p = .280$, $d = 0.44$), whereas children with ADHD walked with higher stride time variability than children without ADHD ($p = .012$, $d = 0.50$). In the present study we additionally included the gait parameters stride length, stride time, and stride velocity variability (see Table 2). While the groups did not differ in stride length ($p = .571$, $d = 0.15$) and stride time ($p = .291$, $d = 0.23$), children with ADHD showed significantly higher stride velocity variability than controls in single-task walking ($p = .012$, $d = 0.68$).

Equipment and measures

All gait analyses were performed according to the European guidelines for spatial-temporal gait analysis (Kressig, Beauchet, European GAITRite Network Group, 2006). Gait was measured using the GAITRite electronic walkway system (GAITRite Platinum; CIR Systems, USA), a 701-cm-long walkway with 23,040 integrated pressure sensors. The validity and reliability of gait assessment using GAITRite for children is well established (Thorpe, Dusing & Moore, 2005). A 1.25-m non-recordable zone was added on each end of the walkway to minimize the effects of acceleration and deceleration. Hence, children walked approximately 10 m per walk comprising on average 8 steps. After each walk, data were analyzed using GAITRite software. The following gait parameters were evaluated: velocity (obtained by dividing the distance traveled by ambulation time expressed in centimeters per second), stride length (the distance between the heel points of two consecutive footfalls of the same

Running head: GAIT AND DUAL-TASKING IN ADHD

foot), stride time (the time elapsed between the first contact of two consecutive footfalls of the same foot expressed in seconds), and gait variability, assessed as stride-to-stride variability in stride velocity, stride length and stride time, using the percentage coefficient of variation (standard deviation/ mean \times 100).

Design and procedure

The concurrent tasks were administered prior to gait assessment for 10 s while children were standing (single-task condition). The concurrent tasks were selected according to previous dual-task related research and included a cognitive and a motor concurrent task. The cognitive task comprised listening to and memorizing digits (digits) (Leitner et al., 2007; Lindenberger, Marsiske, & Baltes, 2000), where children heard a list of randomized digits presented from a computer over loudspeakers that were installed at the front left and front right corner of the laboratory. Afterward, the children were asked to recall the digits and performance on this task was measured as the number of correctly recalled digits. The motor task comprised continuously unfastening and fastening a shirt button at stomach height (button) (Ebersbach, Dimitrijevic, & Poewe, 1995; Yang, Chen, Lee, Cheng, & Wang, 2007) and performance was measured as the number of times the button could be unfastened and fastened.

Before the commencement of the gait measurement children were given one demonstration trial and a practice trial. Then, children performed four trials of walking at their regular pace without any additional task (single-task walking). Afterward, children walked at their regular pace while completing the concurrent cognitive (digits) or motor (button) task (dual-task conditions) with two walks in each condition. Gait parameters were averaged over the trials for further data analysis. In the dual-task conditions participants were not instructed to prioritize either one of the two tasks.

Statistical analysis

Running head: GAIT AND DUAL-TASKING IN ADHD

Effects of dual-task conditions on gait were examined using repeated-measures MANOVAs with group as a between subject factor (ADHD vs. control) and walking condition as a within-subject factor (single-task walking, dual-task walking digits, dual-task walking button) for each gait parameter. Additionally, MANOVAs were performed to assess group differences in concurrent task performance during single-task condition (i.e., when children were standing) and during dual-task conditions.

Significant effects were followed up with Bonferroni corrected post-hoc pairwise comparisons. If an extreme value (defined as a score exceeding 3 *SDs* from the group mean) occurred in the gait parameters, scores were truncated to ± 3 *SD*. The criterion level for statistical significance was set at $p < 0.05$ and the *F* statistic, *p* value (two-tailed), and effect sizes (η^2) are reported.

Results

For spatiotemporal and variability measures of gait, means and standard deviations in single- and dual-task conditions are shown in Table 2.

Please insert Table 2 about here

Statistical results from the repeated-measures MANOVAs for each gait parameter are presented in Table 3. For all gait parameters, a significant within-subject effect of walking condition emerged (Wilks' multivariate test, $F(2, 52) = 19.898$ to 278.25 , $p < .001$, $\eta^2 = .273$ to $.840$). Pairwise comparisons revealed higher velocity, higher stride length, and lower stride time in single-task walking compared to both dual-task walking conditions ($p < .001$), and in the dual-task walking condition digits compared to button ($p < .001$). For all variability measures, pairwise comparisons revealed lower gait variability in single-task walking compared to both dual-task walking conditions ($p < .05$), and in the dual-task condition digits compared to button ($p < .01$). There was no between-subject effect of group nor a significant Walking condition \times Group interaction.

Running head: GAIT AND DUAL-TASKING IN ADHD

For cognitive and motor concurrent task performance during single-task condition (i.e., when children were standing), the MANOVA revealed no significant group differences (Wilks' multivariate test, $F(2, 53) = 1.442, p = .246, \eta^2 = .052$) such that both groups showed similar performance in the number of correctly recalled digits (ADHD: 3.8 ± 0.8 ; controls: 4.2 ± 0.7) and in the number of times the button could be fastened and unfastened (ADHD: 5.1 ± 1.2 ; controls: 5.3 ± 1.5). However, for dual-task conditions, the MANOVA revealed a significant group difference (Wilks' multivariate test, $F(2, 52) = 3.590, p = .035, \eta^2 = .121$), with pairwise comparisons showing that controls recalled significantly more digits (4.6 ± 0.9) than children with ADHD (3.9 ± 1.2) ($p = .015$) whereas the two groups did not differ in the number of times the button could be unfastened and fastened while walking (ADHD: 5.3 ± 1.6 ; controls: 6.0 ± 1.6).

Please insert Table 3 about here

Discussion

This study investigated gait characteristics of school-aged children with ADHD (without or off medication). Previous research has shown that children with ADHD walk with higher gait variability compared to controls (Leitner et al., 2007; Manicolo et al., 2016; Papadopoulos et al., 2014), indicating a less regular walking pattern in children with ADHD compared to typically developing children. Our study extends this research and investigated gait in children with and without ADHD while walking and concurrently performing a cognitive and a motor concurrent task.

Our results showed that dual-task effects on gait are apparent for a cognitive and a motor concurrent task: When memorizing and recalling digits and when unfastening and fastening a button while walking both children with ADHD and typically developing controls showed a decrease in velocity and stride length whereas stride time and all measures of gait variability increased compared to single-task walking. For children with ADHD our study is

Running head: GAIT AND DUAL-TASKING IN ADHD

therefore the first to show that not only a concurrent cognitive task (Leitner et al., 2007) but also a concurrent motor task affects gait performance. Further, our results are in line with previous research showing that in typically developing children, concurrent cognitive (Boon-yong et al., 2012; Huang et al., 2003) and motor tasks (Cherng et al., 2007; Hung et al., 2013) affect gait. Hence, the here reported gait alterations in dual-task conditions indicate that in children with and without ADHD gait is not a fully automatic activity but rather requires executive functions (Woollacott & Shumway-Cook, 2002).

Further, our results showed that children with ADHD and controls did not differ in any gait parameter in both dual-task conditions. This is in contrast to our hypothesis stating that children with ADHD will show more strongly compromised dual-task gait performance compared to children without ADHD. Since impaired executive functions are common for children with ADHD (e.g., Gilberg, 2003; Steger et al., 2001; Wildings, 2005; Willcutt et al., 2005) those results may to some extent contradict previous findings reporting a link between impaired executive functions and poorer gait performance in dual-task conditions among healthy older adults compared to healthy young adults (Beurskens & Bock, 2012) and among clinical adult samples compared to healthy controls (Sheridan et al., 2003; Yogev et al., 2005). However, our results are in line with Leitner et al. (2007) reporting that the effect of dual-tasking on gait was comparable between children with and without ADHD.

Regarding concurrent task performance we found that children with ADHD showed similar performance as controls in recalling digits when standing but recalled significantly fewer digits correctly than controls in the dual-task walking condition. This pattern, however, did not emerge for the task performance in fastening and unfastening a button such that the two groups did neither differ in the number of how many times they fastened and unfastened a button while standing nor while simultaneously walking. Hence, for children with ADHD, the dual-task condition digits may have been more challenging by placing greater demands

Running head: GAIT AND DUAL-TASKING IN ADHD

on executive functions than the dual-task condition button and therefore resulting in degraded performance in the concurrent task digits compared to controls. However, since we were not able to directly test this assumption, further research is needed in order to investigate the contribution of impaired executive functions to task performance in dual-task conditions in children with ADHD.

Finally, our results showed that dual-task effects on walking differed between the two types of concurrent tasks: For children with ADHD as well as for controls the concurrent motor task in which children had to unfasten and fasten a button caused a greater decrease in velocity and stride length, and a greater increase in stride time and gait variability than the concurrent cognitive task in which children had to listen to and memorize digits. This finding indicates that a concurrent motor task may cause greater dual-task gait decrements than a cognitive concurrent task what is in line with previous research (Cherng et al., 2007; Hagmann-von Arx et al., 2016) and may be interpreted from the perspective of the multiple-resource model of attention (Wickens, 1991). The model assumes that attentional resources are divided into various pools depending, for example, on the modality of input and response. Walking requires visual input and further involves the response of moving and controlling body segments, which Cherng et al. (2007) subsumed under the term somatosensation. The motor concurrent task button requires visual input and somatosensory response whereas the concurrent task digits requires auditory input and vocal response. Following the models' assumption, the motor concurrent task button therefore interferes more strongly with walking regarding processing resources than the cognitive concurrent task digits. This may explain why the dual-task effect on gait was greater for the concurrent motor task compared to the cognitive concurrent task in our study.

Our study has strengths and limitations. We consider it a strength that gait characteristics were assessed using the GAITRite system, which has proved to be a valid method of

Running head: GAIT AND DUAL-TASKING IN ADHD

measuring gait parameters in children and offers the possibility of reliably identifying subtle changes in gait (Thorpe et al., 2005). During gait assessment children were wearing their normal clothes and shoes and it was therefore possible to assess gait performance as it is exhibited under daily circumstances. Furthermore, all participating children were screened for DCD in order to exclude children with significant motor deficits, which could have interfered with their gait performance. However, up to 47% of children with ADHD meet diagnostic criteria for DCD (Kadesjö & Gillberg, 2003; Martin, Piek, Baynam, Levy, & Hay, 2010; Tervo, Azuma, Fogas, & Fiechtner, 2002) and our results may not be generalized to individuals with a co-morbid diagnosis. Additionally, children with ADHD were not classified according to any ADHD subtype and it therefore remains subject to future research to investigate whether gait characteristics differ according to a particular ADHD subtype. Furthermore, future research should include further types of concurrent tasks when investigating gait of children with ADHD in dual-task conditions because previous research with typically developing children showed interference effects on gait for visual and auditory concurrent tasks (Huang et al., 2003). Finally, we analyzed temporal and spatial gait parameters as the walkway system GAITRite does not allow the capture of other gait characteristics. Hence, future studies on dual-task walking might investigate further aspects of children's gait as for example kinetic gait parameters (Chester, Tingley, & Biden, 2006).

In conclusion, the results of this study indicate that school-aged children with and without ADHD have difficulty in maintaining their usual walking performance while carrying out a concurrent cognitive or motor task, indicating that walking requires executive functions. Although ADHD has repeatedly been linked to deficits in executive functions (e.g., Gilberg, 2003; Steger et al., 2001; Wildings, 2005; Willcutt et al., 2005), these deficits did not lead to a more strongly compromised gait pattern in dual-task walking in children with ADHD compared to controls. Finally, we found dual-task gait decrements to be larger when

Running head: GAIT AND DUAL-TASKING IN ADHD

walking and concurrently performing a motor compared to a cognitive task. Therefore, our results underscore the importance of taking the type of concurrent task into account when investigating children's gait in a dual-task paradigm. Knowing the effects concurrent tasks may have on the walking performance of children may raise the awareness of how activities should be structured in order to minimize dual-task interference and therefore possibly avoiding accidental injuries. Nonetheless, it remains to be further investigated how the here reported findings for gait in children with and without ADHD in dual-task paradigms extend to other tasks of children's everyday life.

Running head: GAIT AND DUAL-TASKING IN ADHD

References

- American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.
- Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology*, 8, 71–82.
- Beurskens R, & Bock O. (2012). Age-related deficits of dual-task walking: a review. *Neural Plasticity*, 2012,131608.
- Boonyong, S., Siu, K. C., van Donkelaar, P., Chou, L. S, Woollacott, M. H. (2012). Development of postural control during gait in typically developing children: the effects of dual-task conditions. *Gait and Posture*, 35, 428–434.
- Buderath, P., Gartner, K., Frings, M., Christiansen, H., Schoch, B., Konczak, J., & Timmann, D. (2009). Postural and gait performance in children with attention deficit/ hyperactivity disorder. *Gait and Posture*, 29, 249–254.
- Cherng, R. J., Liang, L. Y., Hwang, I. S., & Chen, J. Y. (2007). The effect of a concurrent task on the walking performance of preschool children. *Gait and Posture*, 26, 231–237.
- Chester, V. L., Tingley, M., & Biden, E. N. (2006). A comparison of kinetic gait parameters for 3–13 year olds. *Clinical Biomechanics*, 21, 726–732.
- Ebersbach, G., Dimitrijevic, M. R., Poewe, W. (1995). Influence of concurrent tasks on gait: a dual-task approach. *Perceptual and Motor Skills*, 81, 107–113.
- Fliers, E. A., de Hoog, M. L., Franke, B., Faraone, S. V., Rommelse, N. N., Buitelaar, J. K., et al. (2010). Actual motor performance and self-perceived motor competence in children with attention-deficit hyperactivity disorder compared with healthy siblings and peers. *Journal of Developmental & Behavioral Pediatrics*, 31, 35.

Running head: GAIT AND DUAL-TASKING IN ADHD

- Gillberg, C. (2003). Deficits in attention, motor control, and perception: a brief review. *Archives of Disease in Childhood*, 88, 904–910.
- Glisky, E. L. (2007). Changes in cognitive function in human aging. In D. R. Riddle (Ed.), *Brain aging: models methods, and mechanisms* (pp. 3-20). Boca Raton: CRC Press.
- Hagmann-von Arx, P., Manicolo, O., Lemola, S., & Grob, A. (2016). Walking in school-aged children in a dual-task paradigm is related to age but not to cognition, motor behavior, injuries, or psychosocial functioning. *Frontiers in Psychology*, 7, 352.
- Hagmann-von Arx, P., Manicolo, O., Perkinson-Gloor, N., Weber, P., Grob, A., & Lemola, S. (2015). Gait in very preterm school-aged children in dual-task paradigms. *PLoS ONE*, 10, e0144363.
- Harvey, W. J., & Reid, G. (1997). Motor performance of children with attention deficit hyperactivity disorder: a preliminary investigation. *Adapted Physical Activity Quarterly*, 14, 190–202.
- Harvey, W. J., & Reid, G. (2003). Attention-Deficit/Hyperactivity Disorder: a review of research on movement skill performance and physical fitness. *Adapted Physical Activity Quarterly* 20, 1–25.
- Hausdorff, J. M. (2005). Gait variability: methods, modeling and meaning. *Journal of Neuroengineering and Rehabilitation*, 2, 19.
- Huang, H. J., Mercer, V. S., & Thorpe, D. E. (2003). Effects of different concurrent cognitive tasks on temporal-distance gait variables in children. *Pediatric Physical Therapy*, 15, 105–113.
- Hung, Y. C., Meredith, G. S., & Gill, S. V. (2013). Influence of dual task constraints during walking for children. *Gait and Posture*, 38, 450–454.

Running head: GAIT AND DUAL-TASKING IN ADHD

- Kadesjö, B., & Gillberg, C. (2003). The comorbidity of ADHD in the general population of Swedish school-age children. *Journal of Child Psychology and Psychiatry*, 42(4), 487–492.
- Kaiser, M. L., Schoemaker, M. M., Albaret, J. M., & Geuze, R. H. (2015). What is the evidence of impaired motor skills and motor control among children with attention deficit hyperactivity disorder (ADHD)? Systematic review of the literature. *Research in Developmental Disabilities*, 36, 338–357.
- Kressig, R. W., Beauchet, O., & European GAITRite Network Group (2006). Guidelines for clinical applications of spatio-temporal gait analysis in older adults. *Aging Clinical and Experimental Research*, 18, 174–176.
- Leitner, Y., Barak, R., Giladi, N., Peretz, C., Eshel, R., Gruendlinger, L., & Hausdorff, J. M. (2007). Gait in attention deficit hyperactivity disorder: Effects of methylphenidate and dual tasking. *Journal of Neurology*, 254, 1330–1338.
- Lindenberger, U., Marsiske, M., & Baltes, P. B. (2000). Memorizing while walking: increase in dual-task costs from young adulthood to old age. *Psychology and Aging*, 15, 417.
- Manicolo, O., Grob, A., Lemola, S., & Hagmann-von Arx, P. (2016). Age-related decline of gait variability in children with attention-deficit/hyperactivity disorder: Support for the maturational delay hypothesis in gait. *Gait and Posture*, 44, 245–249.
- Martin, N. C., Piek, J., Baynam, G., Levy, F., & Hay, D. (2010). An examination of the relationship between movement problems and four common developmental disorders. *Human Movement Science*, 29, 799–808.
- Papadopoulos, N., McGinley, J. L., Bradshaw, J. L., & Rinehart, N. J. (2014). An investigation of gait in children with Attention Deficit Hyperactivity Disorder: a case controlled study. *Psychiatry Research*, 218, 319–323.

Running head: GAIT AND DUAL-TASKING IN ADHD

- Pastor, P. N., & Reuben, C. A. (2006). Identified attention-deficit/hyperactivity disorder and medically attended, nonfatal injuries: US school-age children, 1997-2002. *Ambulatory Pediatrics, 6*, 38-44.
- Petermann, F., & Petermann, U. (2011). *Wechsler Intelligence Scale for Children (WISC-IV)*. Frankfurt, Germany: Pearson Assessment.
- Petermann, F. (2008). *Movement Assessment Battery for Children 2nd edition*. Frankfurt, Germany: Pearson Assessment.
- Piek, J. P., Pitcher, T. M., & Hay, D. A. (1999). Motor coordination and kinaesthesia in boys with attention deficit-hyperactivity disorder. *Developmental Medicine & Child Neurology, 41*, 159-165.
- Polanczyk, G., & Rhode, L. A. (2007). Epidemiology of attention-deficit/hyperactivity disorder across the lifespan. *Current Opinion in Psychiatry, 20*, 386-392.
- Raberg, T., & Wimmer, H. (2003). On the automaticity/ cerebellar deficit hypothesis of dyslexia: balancing and continuous rapid naming in dyslexic and ADHD children. *Neuropsychologia, 41*, 1493-1497.
- Racine, M. B., Majnemer, A., Shevell, M., & Snider, L. (2008). Handwriting performance in children with attention deficit hyperactivity disorder (ADHD). *Journal of Child Neurology, 23*, 399-406.
- Schaefer, S., Lövdén, M., Wieckhorst, B., & Lindenberger, U. (2010). Cognitive performance is improved while walking: Differences in cognitive-sensorimotor couplings between children and young adults. *European Journal of Developmental Psychology, 7*, 371-389.
- Sheridan, P. L., Solomont, J., Kowall, N., & Hausdorff, J. M. (2003). Influence of executive function on locomotor function: divided attention increases gait variability in Alzheimer's disease. *Journal of the American Geriatrics Society, 51*, 1633-1637.

Running head: GAIT AND DUAL-TASKING IN ADHD

- Shum, S., & Pang, M. Y. (2009). Children with attention deficit hyperactivity disorder have impaired balance function: Involvement of somatosensory, visual, and vestibular systems. *The Journal of Pediatrics*, 155, 245–249.
- Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E. S., & Hausdorff, J. M. (2006). Dual-tasking effects on gait variability: the role of aging, falls, and executive function. *Movement Disorders*, 21, 950–957.
- Steger, J., Imhof, K., Coutts, E., Gundelfinger, R., Steinhausen, H. C., & Brandeis, D. (2001). Attentional and neuromotor deficits in ADHD. *Developmental Medicine & Child Neurology*, 43, 172–179.
- Thorpe, D. E., Dusing, S. C., & Moore, C. G. (2005). Repeatability of temporospatial gait measures in children using the GAITRite electronic walkway. *Archives of Physical Medicine and Rehabilitation*, 86, 2342–2346.
- Tervo, R. C., Azuma, S., Fogas, B., & Fiechtner, H. (2002). Children with ADHD and motor dysfunction compared with children with ADHD only. *Developmental Medicine & Child Neurology*, 44, 383–390.
- Tsang, P. S. (2013). Aging and attentional control. *The Quarterly Journal of Experimental Psychology*, 66, 1517–1547.
- Wickens, C. D. (1991). Processing resources in attention. In D. L. Damos (Ed.), *Multiple-task performance* (pp. 3–34). Washington, DC: Taylor & Francis.
- Wilding, J. (2005). Is attention impaired in ADHD? *British Journal of Developmental Psychology*, 23, 487–505.
- Willcutt, E. G., Doyle, A. E., Nigg, J. T., Faraone, S. V., & Pennington, B. F. (2005). Validity of the executive function theory of attention-deficit/hyperactivity disorder: a meta-analytic review. *Biological Psychiatry*, 57, 1336–1346.

Running head: GAIT AND DUAL-TASKING IN ADHD

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait and Posture*, *16*, 1–14.

Yang, Y. R., Chen, Y. C., Lee, C. S., Cheng, S. J., & Wang, R. Y. (2007). Dual-task-related gait changes in individuals with stroke. *Gait and Posture*, *25*, 185–190.

Yogev, G., Giladi, N., Peretz, C., Springer, S., Simon, E. S., & Hausdorff, J. M. (2005). Dual tasking, gait rhythmicity, and Parkinson's disease: which aspects of gait are attention demanding? *European Journal of Neuroscience*, *22*, 1248–1256.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders*, *23*, 329–342.

Table 1
Demographic characteristics of children with attention-deficit hyperactivity disorder (ADHD) and controls.

Characteristic	ADHD (<i>n</i> = 30)	Controls (<i>n</i> = 28)	<i>p</i>
Age (years)	10.9 (1.4)	10.8 (1.4)	.847
Sex (girls:boys)	5:25	3:25	.512
Height (cm)	142.7 (29.7)	140.3 (29.3)	.761
Weight (kg)	40.4 (16.8)	36.8 (12.0)	.361
Leg length (cm) ^a	75.4 (16.6)	74.7 (16.9)	.862

Note. Data are mean (SD) or number; *p* values are given for independent *t* test, or χ^2 test.

^aLeg length was measured with footwear from greater trochanter to the floor, bisecting the lateral malleolus.

Table 2
Means (and standard deviations) of gait parameters for
children with attention-deficit hyperactivity disorder
(ADHD) and controls in single- and dual-task conditions

Gait parameters	ADHD ($n = 30$)	Controls ($n = 28$)
Velocity (cm/s)		
Single task	127.75 (21.76)	131.51 (15.64)
Dual task: digits	101.62 (19.51)	103.74 (15.28)
Dual task: button	82.57 (20.24)	88.46 (16.74)
Stride length (cm)		
Single task	130.30 (16.03)	132.47 (12.61)
Dual task: digits	113.65 (15.14)	114.18 (11.31)
Dual task: button	99.73 (17.30)	103.69 (15.40)
Stride time (s)		
Single task	1.04 (0.10)	1.01 (0.08)
Dual task: digits	1.13 (0.13)	1.11 (0.10)
Dual task: button	1.25 (0.20)	1.19 (0.10)
Stride velocity variability (%)		
Single task	3.05 (1.43)	2.25 (0.83)
Dual task: digits	3.69 (1.26)	3.64 (1.99)
Dual task: button	5.89 (3.98)	5.21 (2.84)
Stride length variability (%)		
Single task	2.28 (1.13)	1.88 (0.61)
Dual task: digits	2.52 (0.97)	2.61 (1.50)
Dual task: button	4.72 (4.00)	4.48 (3.95)
Stride time variability (%)		
Single-task	2.45 (1.50)	1.67 (0.55)
Dual task: digits	2.69 (0.92)	2.48 (1.58)
Dual task: button	4.54 (2.78)	4.02 (2.55)

Note. Digits = listening to and memorizing digits; Button = unfastening and fastening a button.

Table 3

Statistical results from the repeated-measures MANOVAs comparing the single- to the dual-task conditions for each gait parameter.

Gait parameter	Walking condition			Group ^a			Walking condition \times Group		
	<i>F</i>	<i>p</i>	η^2	<i>F</i>	<i>p</i>	η^2	<i>F</i>	<i>p</i>	η^2
Velocity	278.253	<.001	.840	.876	.354	.016	.265	.768	.005
Stride length	260.721	<.001	.831	.622	.434	.012	.319	.728	.006
Stride time	88.62	<.001	.626	1.141	.290	.290	1.205	.304	.022
Stride velocity variability	28.065	<.001	.346	1.57	.216	.029	.517	.598	.010
Stride length variability	19.898	<.001	.273	.243	.624	.005	.211	.810	.004
Stride time variability	33.615	<.001	.388	2.364	.130	.043	.634	.532	.012

^a Children with attention-deficit hyperactivity disorder vs. controls.

APPENDIX F: Selbständigkeitserklärung

Hiermit erkläre ich, dass ich die Dissertation „Gait in Single- and Dual-Task Conditions: Investigations of Children With and Without Developmental Risks and Disorders“ selbstständig verfasst und nur unter Verwendung der angegebenen Quellen und Hilfsmittel angefertigt habe. Alle wörtlichen oder sinngemässen Zitate sind als solche gekennzeichnet. Die zur Promotion eingereichten Zeitschriftenbeiträge wurden in Zusammenarbeit mit den jeweiligen Co-Autorinnen und Co-Autoren angefertigt.

Basel, im April 2016

Olivia Manicolo

APPENDIX G: Curriculum Vitae

Name: Olivia Franziska Josephine Manicolo

Nationality: Swiss (Münchenstein, BL)

Date of Birth: September 15, 1987

Higher Education

2012–2016 Research assistant and doctoral student at the Department of Psychology,
Division of Developmental and Personality Psychology, University of Basel,
Switzerland

2010–2012 Master of Science in Psychology, Major in Personality and Developmental
Psychology, University of Basel, Switzerland

2007–2010 Bachelor of Science in Psychology, University of Basel, Switzerland

School Education

2003–2006 High School, Münchenstein, Switzerland

1999–2003 Secondary School, Münchenstein, Switzerland

1992–1999 Kindergarten and Primary School, Münchenstein, Switzerland

Internships

2011 Intern at Heilpädagogische Schule Münchenstein, Switzerland

2010 Intern at Schulpsychologischer Dienst Muttens, Switzerland